ENERGY MANAGEMENT IN SECONDARY DISTRIBUTION NETWORK USING PHASE BALANCING ALGORITHM

Thesis
Submitted in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY
by

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June, 2018

DECLARATION

by the Ph.D. Research Scholar

I hereby declare that the Research Thesis entitled *Energy Management in Secondary Distribution Network using Phase Balancing Algorithm* which is being submitted to the National Institute of Technology Karnataka, Surathkal in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy in Electrical and Electronics Engineering is a bonafide report of the research work carried out by me. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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CERTIFICATE

This is to certify that the Research Thesis entitled *Energy Management in Secondary Distribution Network using Phase Balancing Algorithm* submitted by Swapna M (Register Number: 121178EE12F04) as the record of the research work carried out by her, is accepted as the Research Thesis submission in partial fulfillment of the requirements for the award of degree of Doctor of Philosophy.

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Dedicated to

My Parents, Siblings

&

Mentor (R. Srinivasa Rao)

ABSTRACT

The ever-increasing power demand, depleting fossil fuels, earnest environmental concerns have led to the concept of energy management. This includes measurement, identification and rectification of power losses. Among the three functional areas of electrical utility, the distribution sector needs more attention as it is complex and contributes to high technical losses. In order to supplement these losses due to transformers, conductors, low power factor, etc. and thereby to enhance the reliability and efficiency of the distribution system, a few well-established concepts/ algorithms/ techniques have been applied. However, the losses due to unbalanced loading among the phases at each bus are overlooked. With this motivation to consider and study the effect of phase balancing by taking into account three-phase consumer service mains (CSMs) and balancing at each bus, algorithms are proposed. The rationale behind the proposed algorithms lies in the fact that it is formulated using the non-iterative computational method as it addresses single bus at a time.

Further, the proposed algorithm is combined with backward sweep technique resulting in an effective reduction of neutral current and branch currents. Besides, a method is proposed for the selection of the phase arrangement resulting in reduced service interruptions and minimum losses. The proposed algorithms are tested in MATLAB considering the IEEE 13-bus and 123-bus test feeders and a typical practical system at Mysuru, India. The performance of the algorithms is evaluated following through various cases comprising single-phase CSMs alone, three-phase and single-phase CSMs, three-phase and single-phase CSMs by considering three-phase load as lumped load while balancing single-phase CSMs, three-phase and single-phase CSMs by considering feeder laterals as movable at each bus respectively, with an objective of line loss reduction, minimum number of phase moves, branch current and neutral current reduction with enhanced voltage profile. Finally, the corresponding results are presented.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

Energy management has become a defacto standard to contribute to the Country's economic growth, environmental safety and to overcome energy requirements. The increase in population, urbanisation, depleting fossil fuels and increased environmental concerns lead to the concept of energy saving and power generation utilizing green resources. The most effective approach for meeting energy demands is an efficient use of energy and its conservation. This will leads to the wise use of energy resources and energy management. For the same, Government of India has also taken steps to manage energy by imposing mandatory energy audit and energy conservation regulations.

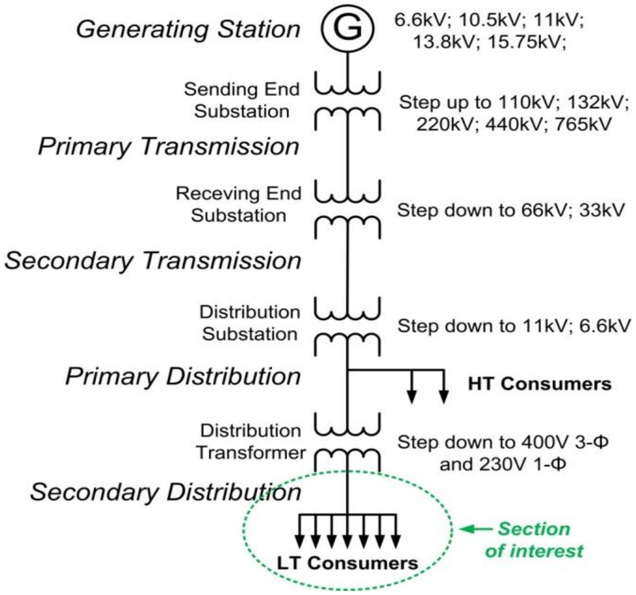
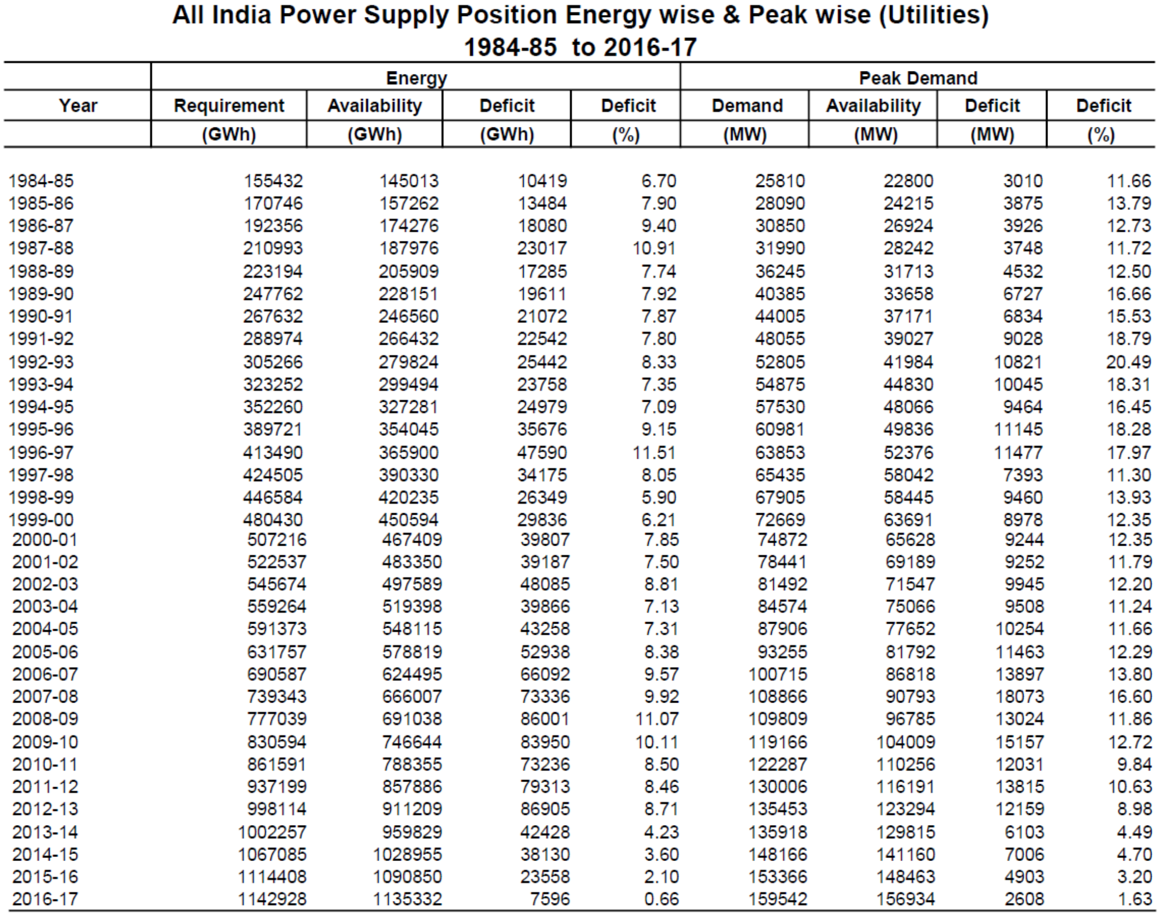


Figure 1. 1 Single Line diagram of the power system.

The typical power system comprising generation, transmission and distribution (T&D) is shown in Fig.1.1 and shows the different levels of voltage at each step. The electrical energy produced at power stations has to be supplied to the consumer by meeting power quality standards. The T&D network plays a crucial role in supplying quality power to the consumers from the remotely located generating station. In the process of transmission of power, we come across a lot of losses due to transformers, lines, protection equipment, power factor, etc. Fig 1.2 shows the peak demand and the available generation statistics of India. In order to meet the peak demand, the stated deficiency has to be addressed either by an additional generation or by conserving power.



All India Power Supply Position Energy wise & Peak wise (Utilities)
1984-85 to 2016-17

	Energy				Peak Demand			
Year	Requirement (GWh)	Availability (GWh)	Deficit (GWh)	Deficit (%)	Demand (MW)	Availability (MW)	Deficit (MW)	Deficit (%)
1984-85	155432	145013	10419	6.70	25810	22800	3010	11.66
1985-86	170746	157262	13484	7.90	28090	24215	3875	13.79
1986-87	192356	174276	18080	9.40	30850	26924	3926	12.73
1987-88	210993	187976	23017	10.91	31990	28242	3748	11.72
1988-89	223194	205909	17285	7.74	36245	31713	4532	12.50
1989-90	247762	228151	19611	7.92	40385	33658	6727	16.66
1990-91	267632	246560	21072	7.87	44005	37171	6834	15.53
1991-92	288974	266432	22542	7.80	48055	39027	9028	18.79
1992-93	305266	279824	25442	8.33	52805	41984	10821	20.49
1993-94	323252	299494	23758	7.35	54875	44830	10045	18.31
1994-95	352260	327281	24979	7.09	57530	48066	9464	16.45
1995-96	389721	354045	35676	9.15	60981	49836	11145	18.28
1996-97	413490	365900	47590	11.51	63853	52376	11477	17.97
1997-98	424505	390330	34175	8.05	65435	58042	7393	11.30
1998-99	446584	420235	26349	5.90	67905	58445	9460	13.93
1999-00	480430	450594	29836	6.21	72669	63691	8978	12.35
2000-01	507216	467409	39807	7.85	74872	65628	9244	12.35
2001-02	522537	483350	39187	7.50	78441	69189	9252	11.79
2002-03	545674	497589	48085	8.81	81492	71547	9945	12.20
2003-04	559264	519398	39866	7.13	84574	75066	9508	11.24
2004-05	591373	548115	43258	7.31	87906	77652	10254	11.66
2005-06	631757	578819	52938	8.38	93255	81792	11463	12.29
2006-07	690587	624495	66092	9.57	100715	86818	13897	13.80
2007-08	739343	666007	73336	9.92	108866	90793	18073	16.60
2008-09	777039	691038	86001	11.07	109809	96785	13024	11.86
2009-10	830594	746644	83950	10.11	119166	104009	15157	12.72
2010-11	861591	788355	73236	8.50	122287	110256	12031	9.84
2011-12	937199	857886	79313	8.46	130006	116191	13815	10.63
2012-13	998114	911209	86905	8.71	135453	123294	12159	8.98
2013-14	1002257	959829	42428	4.23	135918	129815	6103	4.49
2014-15	1067085	1028955	38130	3.60	148166	141160	7006	4.70
2015-16	1114408	1090850	23558	2.10	153366	148463	4903	3.20
2016-17	1142928	1135332	7596	0.66	159542	156934	2608	1.63

Figure 1.2 All India supply position energy wise and peak wise (www.cea.nic.in/reports/others/planning/pdm/growth_2017.pdf)

The Table 1.1 below shows the various components of power system losses. It is evident from the Table 1.1 that the losses in the distribution system are relatively high as compared to other loss contributors. Fig. 1.3 depicts the T&D losses in chronological order after independent India.

Table 1. 1 Comparative losses in various sections of power systems

Section	**%Losses**
Total System	100
Generation Step up Transformers and Transmission Sub-station	11.58
Transmission and Sub-transmission Lines	20.66
Sub-transmission or Grid Sub-stations	12.85
Primary feeders and line equipment	25.27
Distribution Transformers	17.22
Secondary and Service lines and Grounds	11.82
Meters	0.6

These losses are categorized into :

- Conductor Impedance
    - Unbalanced loading
    - Network designing
    - I^2R loss
- Improper Earthing
- Low power factor
    - Inductive loads
    - Converters
- Equipment losses
    - Distribution transformer core and winding losses
    - Energy metering losses
    - Protection and monitoring device losses

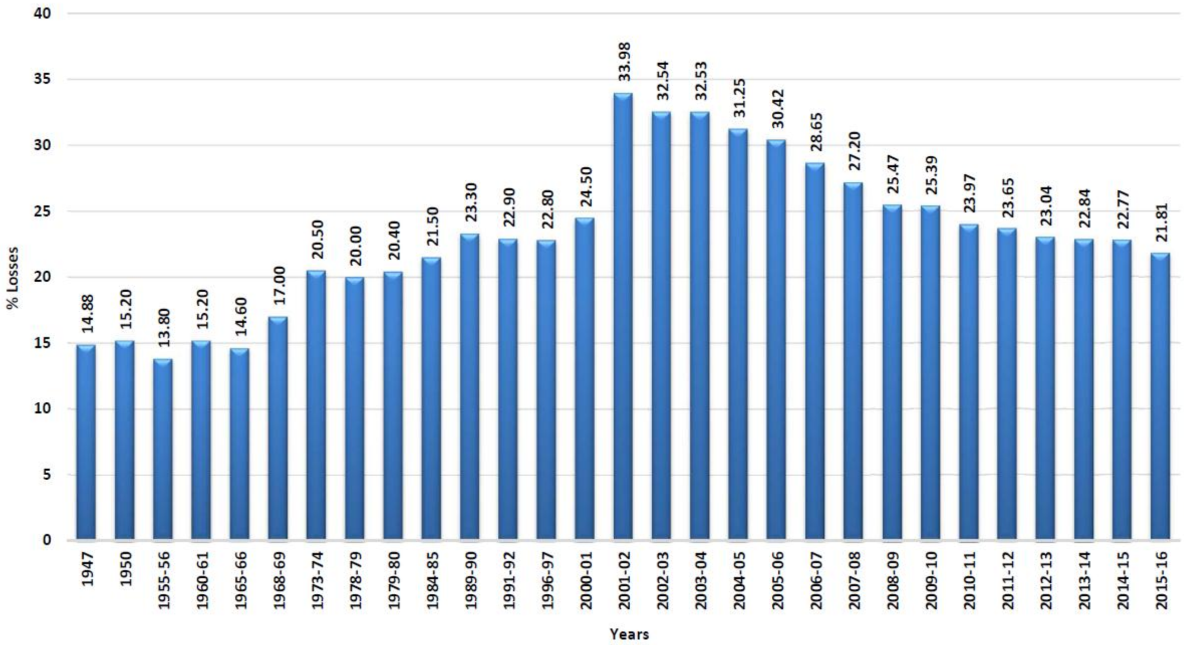


Figure 1. 3 All India transmission and distribution losses (www.cea.nic.in/reports/others/planning/pdm/growth_2017.pdf)

The distribution line losses are predominant amongst T&D losses as listed in Table 1.2 and are to be attended in order to make the system efficient by reducing the losses. The loss due to unbalanced loading is one of the key contributors to the overall distribution loss, the methods ameliorating the same need more emphasis.

Table 1. 2 Guidelines for development of sub transmission and distribution system

Zone	**System Elements**	**Power loss**
A	Step up transformer & EHV transmission system	0.50 % to 1.00%
B	Transformation to intermediate voltage level, transmission system & step	1.5% to 3.00%
C	Sub transmission system and step down to distribution voltage level.	2.25% to 4.50%
D	Distribution lines and service connections.	4.00% to 7.00%
	TOTAL LOSSES	8.25% to 15.50%

Secondary/ Low voltage (LV) Distribution networks are often unbalanced by feeder laterals design/structure (with single-phase and two-phase feeder laterals), and unbalanced loading by Consumer Service Mains (CSM) (single-phase, two-phase and three-phase CSM) as shown in Fig.1.4.

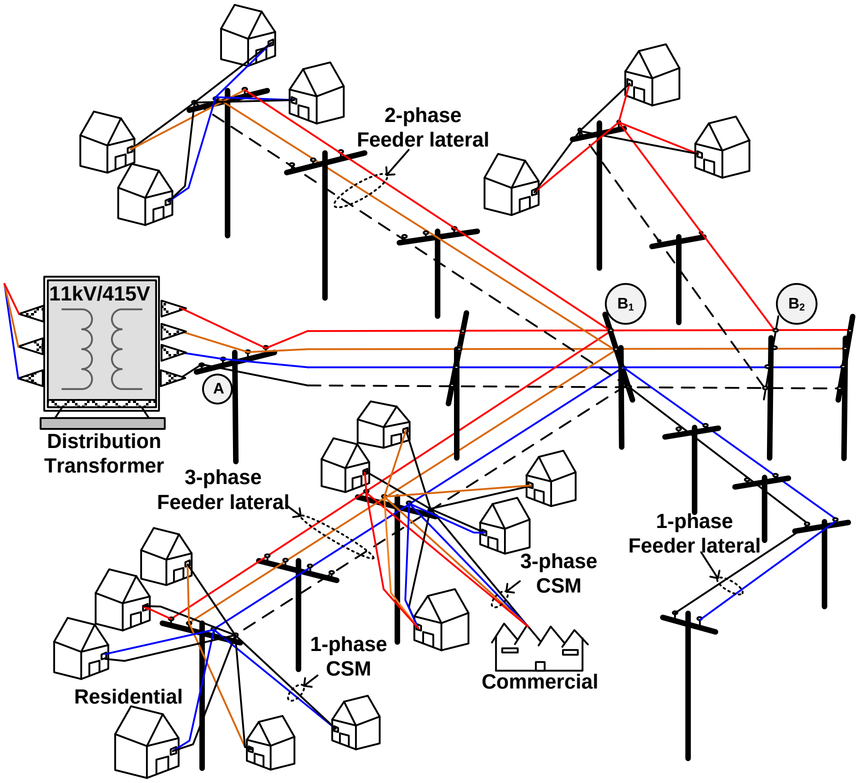


Figure 1. 4 Schematic diagram of secondary/ LV distribution network.

The effects of unbalance on system performance are as follows:

- In an unbalanced system the loaded phase when reaches maximum allowable capacity of the serving equipment or conductors, reduces the system peak load supplying capability.
- The transformer and other equipment life span degrades, if one phase is overloaded because of unbalance.

- As loss is proportional to the square of the current, the loss in the heavily loaded phase rapidly increases with the unbalance, in turn neutral current (due to phase unbalance) further increases the conductor loss.
- The circuit results in excessive voltage drop in the heavily loaded phase which gives rise to poor voltage regulation.
- System protection is also affected by the unbalance operation.

This unbalance in the system can be solved mainly using two approaches:

- Network reconfiguration: It is carried out at the system level by proper switching of sectionalizing and tie switches. The load from the heavily loaded area is transferred to the lightly loaded area.
- Phase balancing: It is carried out at feeder level by rephasing the CSM loads among the phases with a motto to have all three phases equally loaded.

Among the approaches mentioned above, the former leads to heavy current flow and voltage unbalance in some cases, which may not result in effective balancing among the phases as it addresses unbalance due to feeder laterals. Whereas, the latter approach reduces the unbalance problem at the location of unbalance instigation (unbalanced loading by CSMs).

The phase balancing carried out at different levels with reference to the Fig. 1.4 is categorized as:

- *Substation alone balancing*: Balancing at feeder originating bus (similar to bus A) alone.
- *Partial feeder balancing*: Balancing at monitored buses (like B1 or B2) individually or collectively.
- *Whole feeder balancing*: Balancing at each candidate bus.

Phase balancing by empirical methods is time consuming, labor intensive, erroneous and unreliable due to lot of power interruptions. Further, because of the time varying nature of loads, optimization of CSM phase arrangement is complex and tedious to solve using the predictable methods. Automation scheme (using artificial intelligence, communication and power electronic equipment) is employed in distribution system to cope with distribution complexities for CSM phase arrangement manually (Ukil, et. al., 2006). In the automated system, central computing unit takes secondary CSM load consumption information and transmits control signal to load selector switches for rephasing of CSM (Siti, et. al., 2011). Fig. 1.5 shows a typical radial distribution system with l primary feeders F_{p1}, F_{p2},…F_{pl} and for each primary feeder there are n secondary feeders (which step down the voltage further to 230V/415V) to which CSMs are connected through Load Selector Switch (LSS). In this scheme, CSM rephasing is carried out at zero crossing to avoid voltage spikes.

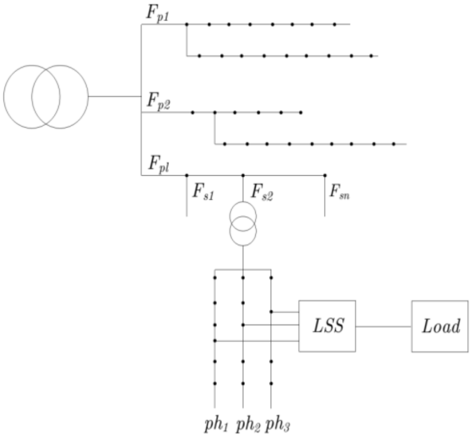


Figure 1. 5 General representation of LSS for secondary distribution system.

Implementation of automatic load balancing is possible by developing algorithm to attain most favourable solution for rearrangement of CSM connections on Low Voltage (LV)/secondary distribution feeder. The various existing phase balancing solutions mentioned in literature are discussed below.

1.2 LITERATURE REVIEW

Phase balancing algorithms existing in literature are categorized into two techniques: Programming techniques and Phase balancing techniques. To compute the phase rearrangement of CSM for unbalanced distribution network, authors have formulated using mixed integer programming technique (Zhu, et. al., 1998), simulated annealing (Zhu, et. al., 1998), genetic algorithm (Gandomkar, 2004), (Chen and Cherng, 2000), heuristic backtracking search (Lin, et. al., 2005), (Huang, et. al., 2008), immune algorithm (Huang, et al., 2008), bacterial foraging oriented by particle swarm optimization (Hooshmand and Soltani, 2012), fuzzy logic (Ukil and Siti, 2008), (Siti, et. al., 2009) (Chitra and Neelaveni, 2011), automated mapping, facilities management, geographic information system (Kuo and Chao, 2010), hybrid greedy fuzzy logic (Sathiskumar, et. al., 2011) and self-adaptive hybrid differential evolution (Sathiskumar, et. al., 2012) algorithms.

Different phase balancing techniques addressed in literature are: the critical branch phase balancing of single-phase CSM loads with the objective of minimizing the maximum unbalanced flow of branch current is computed in (Zhu, et. al., 1998) and (Khodr, et. al., 2006). The average unbalance per phase is calculated and compared with the threshold value, further a fuzzy logic technique is applied for load balancing in (Siti, et. al., 2007), (Ukil and Siti, 2008). The phase balancing to minimize power loss and phase current deviation is presented in (Gandomkar, 2004), (Sathiskumar, et. al., 2012), (Dilek, et. al., 2001). The Phase Unbalance Index (PUI) is mentioned in (Lin et. al., 2005), (Wang, et. al., 2013), multi objective function are reported in (Siti, et. al., 2011), (Hooshmand and Soltani, 2012), (Schweickardt, et. al., 2011), utilization factor (Karim, et. al., 2015). Except for BF-PSO (Hooshmand and Soltani, 2012) algorithm which is developed for both radial and mesh distribution network configurations, all other methods are developed for radial distribution network configuration only. An algorithm using fuzzy logic (Hooshmand and Soltani, 2012), (Ukil and Siti, 2008) and (Siti, et. al., 2009) rephases CSMs at various buses to achieve balancing at point A as shown in Fig. 1.4.The detailed formulations pertaining to the above discussed techniques are enlisted in Table 1.3.

Table 1. 3 Phase balancing technique formulations

<table>
<tr><th><i>Technique</i></th><th><i>Author (Year)</i></th><th><i>Formulae</i></th></tr>
<tr><td>Difference of flow currents in phase</td><td>Zhu et al(1998) and Khodr et al (2006)</td><td>Minimize U_j subject to
$\max\{|I_{j,a}-I_{j,c}|,|I_{j,b}-I_{j,c}|,|I_{j,a}-I_{j,b}|\}=U_j$
$I_{j,\Phi}=\sum_{k} I_{k,j}+\Pi_{j,1}^{i} d_{j,1}+\Pi_{j,2}^{i} d_{j,2}+\Pi_{j,3}^{i} d_{j,3}$
$\Pi_{j,1}^{i}+\Pi_{j,2}^{i}+\Pi_{j,3}^{i}=1 \text{ for all } \Phi=a,b,c$
$\Pi_{a,w}^{i}+\Pi_{b,w}^{i}+\Pi_{c,w}^{i}=1 \text{ for all } w=a,b,c$
$I_{j,j} \le C_j$
$\Pi_{j,w}^{i} \in \{0,1\} \text{ for all } i$
where <i>j</i> is any monitored bus, U_j is the unbalanced flow on branch <i>j</i>, $I_{j,\varphi}$ is the φ phase flow on branch <i>j</i>, $\Pi^{i}_{\varphi\omega}$ is the decision variable for ωth load tapping to phase φ at node <i>I</i>, C_j is the phase line capacity of branch <i>j</i>.</td></tr>
<tr><td><i>Remarks</i></td><td colspan="2">• Maximum unbalanced flow of branch current is computed from difference of phase currents and it is optimised by considering following constraints.
• Each Phase has a load assigned
• Each load is only assigned to a phase
• Line capacity constraints</td></tr>
<tr><td>Average Unbalance per phase</td><td>Siti et al (2007a,2007b) and Ukil et al(2008)</td><td>$\mathrm{AU/ph}=\frac{|L_{\mathrm{ph,a}}-L_{\mathrm{ph,b}}|+|L_{\mathrm{ph,b}}-L_{\mathrm{ph,c}}|+|L_{\mathrm{ph,c}}-L_{\mathrm{ph,a}}|}{3}$
where $L_{\mathrm{ph,a}}$, $L_{\mathrm{ph,b}}$, $L_{\mathrm{ph,c}}$ are the power drawn from the phase A,B,C respectively.</td></tr>
</table>

Remarks	- Average unbalance per phase is compared with its threshold value. If value is below threshold value further phase balancing is not required else diverted to fuzzy logic based load balancing. - Input given to fuzzy is total phase load (KW) for each one of 3 phases, the resulted output of the fuzzy step is the load change values i.e., negative value for load releasing and positive value for load receiving.	
Power Loss	Gandomkar (2004)	$F = \sum_{i=1}^{l} I_{ai}^2 R_{ai} + I_{bi}^2 R_{bi} + I_{ci}^2 R_{ci} + I_{ni}^2 R_{ni}$ where I_{ai}, I_{bi}, I_{ci} are the currents of i^{th} segment of LV network for A, B, C phases, R_{ai}, R_{bi}, R_{ci} are the resistances of i^{th} segment of LV network for A, B, C phases, I_{ni}, R_{ni} are the neutral current and resistance of i^{th} segment, l is themaximum segment number of LV network
Remarks	- Minimize power loss F subjected to - Node voltage between upper and lower limit, - Conductors capacity Load phase either Single or double phase. Re-phasing number(s)	
Power Loss	Echeverri et al (2012)	$\min \sum_{t}^{Nt} T_t \sum_{i=1}^{N-1} R_i \frac{P_{it}^2 + Q_{it}^2}{V_{it}^2}$ $P_{kt}^{spe} - P_{calc}(V_{kt}, \theta_{kt}, \beta, H) = 0$ $Q_{kt}^{spe} - Q_{calc}(V_{kt}, \theta_{kt}, \beta, H) = 0$ $v_k^{\min} < v_k < v_k^{\max}$ $P^{\min} < P_{it} < P^{\max}$ where P_{it} and Q_{it} are the active and reactive power flow in line i for load level t, R_i is the resistance of line i, P^{spe}_{kt} and Q^{spe}_{kt} are the specified values of the active and reactive power injections in node k for load level t, V_{kt} and θ_{kt} represent the voltage magnitude and angle at

		node k for load level t, N_t is number of load levels considered in load duration curve $N - 1$ is the number of lines of the system.
Phase current deviation	Dilek et al (2001) and Sathiskumar et al (2012)	$C = \min\,(DI_m)$ subject to $\lvert V_{\min}\rvert < \lvert V_{nb}\rvert \pounds \lvert V_{\max}\rvert$ $\lvert I_{\max}\rvert > \lvert I_K\rvert$ with $DI_j = \max(\lvert Dev_a^j\rvert, \lvert Dev_b^j\rvert, \lvert Dev_c^j\rvert)$ $Dev_i^j = \frac{I_{ph,i}^j}{I_{ave}^j} - 1$ $I_{\mathrm{ave}} = \frac{I_{\mathrm{ph,a}} + I_{\mathrm{ph,b}} + I_{\mathrm{ph,c}}}{n_{\mathrm{ph}}}$ where Dev_a, Dev_b, Dev_c are the phase current deviations of the phases A, B, C, DI_j refers to maximum deviation index of jth node, $I_{ph,a}$, $I_{ph,b}$, $I_{ph,c}$ are the phase currents of the phases A,B,C , j = nodes m, n, k, . . . , nb, k = 1, 2, 3, 4, . . . , nl, n_{ph} = number of phases, nb = total number of buses in the system, nl = total number of lines in the system, $V_{\max}$ = maximum bus voltages limit, $V_{\min}$ = minimum bus voltages limit
Phasing unbalance index (PUI)	Lin et al(2005) and Wanga et al(2013)	$PUI_j = \frac{\max\left(\lvert I_a^j - I_{\mathrm{avg}}^j\rvert, \lvert I_b^j - I_{\mathrm{avg}}^j\rvert, \lvert I_c^j - I_{\mathrm{avg}}^j\rvert\right)}{I_{\mathrm{avg}}^j}´\ 100\ \%$ Where I_{ja}, I_{jb}, I_{jc} are loadings on phase A, B, C at node j, I^j_{avg} is the average phase current
Remarks	PUI for phase balancing with a assumption of one service lateral at each node. Maximum PUI lateral is rephrased by considering minimum PUI later as base branch. The following operation constraints are considered for rephasing.	

	1. No main transformers, feeders and line switches are overloaded after rephasing. 2. Radial network configuration must be maintained for distribution feeders. 3. All service zones are connected and served by the feeder.	
Multi objective optimization	Schweickardt et al(2011)	$\min\left\{ Loss_T ; I(\Delta u); \left\| I_{[o]} \right\|_f \right\}$ $\left\|\mathrm{I}_{[A]}\right\|_f \leq I_{Max}$; $\left\|\mathrm{I}_{[\mathrm{B}]}\right\|_f \leq I_{Max}$; $\left\|\mathrm{I}_C\right\|_f \leq I_{Max}$ the sub index *f* is the output of substation connected to the principal feeder of the system, $Loss_T$ is the total active power loss of the system, $I(\Delta)$ is voltage drop based index. $I_{[0]f}$ (homopolar component) satisfy the equation $\left\|I_{[A]}\right\|_f + \left\|I_{[B]}\right\|_f + \left\|I_{[C]}\right\|_f = 3X\left\|I_{[O]}\right\|_f$ If system is balanced, then $\|I_{[o]f}\| = 0$
	Willy Mukwanga Siti et al(2011)	$\min J_{oj} = J + J_n + l\, I^0_{ph} + l\, I^-_{ph}$ Where J is the phasor current unbalance relationship, J_n is the neutral current of an unbalanced circuit, I^o_{ph} and I^-_{ph} are the Zero and negative sequence currents of an unbalanced circuit respectively $\min J = \left\| \begin{matrix} I_{ph,1k} - I_{ph,2k} \\ I_{ph,1k} - I_{ph,3k} \\ I_{ph,2k} - I_{ph,3k} \end{matrix} \right\|$ $\min J_n = \left[I_N^2 - \left((I_{ph,ak} - I_{ph,bk})^2 + (I_{ph,ak} - I_{ph,ck})^2 + (I_{ph,bk} - I_{ph,ck})^2 \right) \right]^2$
	Hooshmand et al (2012a, 2012b)	The four objectives are fuzzified and then integrated as the fuzzy multi-objective function *Neutral current of supporting feeder*

		$I_N = I_a + I_b + I_c$ *Average voltage drop* of *i* th node $(V_d)_i = \frac{1}{3}\sum_{k=a}^{c}(V_n - (V_k)_i)/V_n$ *Average voltage drop* $(V_d)_{\text{avg}} = \frac{1}{n}\sum_{i=1}^{n}(V_d)_i) \times 100\ \%$ Rephasing Cost, customer service interruption cost at node *i* is $CIC_i = \left(\sum_{j=1}^{k} c_j x L_J\right) \times t_i$ where k is the number of nodes under the effect of rephasing at node *i*, C_j is the interruption cost of each kWh for *j* node on $CIC_t = \sum_{k=1}^{p} CIC_k$ $RC_t = CIC_t + CL_t$ where CL_t is the labour cost in the whole nodes in which rephasing is performed *Power Losses Cost* $P_{\text{loss}} = \sum_{j=1}^{b} i_j^{*} \times R_j \times i_j$ *Proposed Objective Function* $\text{OF} = w_1 \times I_N + w_2 \times (V_d)_{\text{avg}} + w_3 \times P_{\text{loss}} + w_4 \times RC_t$ $w_1 + w_2 + w_3 + w_4 = 1$ $V_{K_{\min}} < V_K < V_{K_{\max}}, \quad K = 1,2,.........,n$

MicroFITs (Micro Feed in Tariff) in the phase balancing problem	Haytham, et. al., (2014)	$I^a_{h_{unbalance}} = \frac{\left\lvert \lvert I^a_h \rvert - I_{h_{avg}} \right\rvert}{I_{h_{avg}}} ' \ 100$ $I^b_{h_{unbalance}} = \frac{\left\lvert \lvert I^b_h \rvert - I_{h_{avg}} \right\rvert}{I_{h_{avg}}} ' \ 100$ $I^c_{h_{unbalance}} = \frac{\left\lvert \lvert I^b_h \rvert - I_{h_{avg}} \right\rvert}{I_{h_{avg}}} ' \ 100$ where $I_h\text{avg} = \frac{I^a_h + I^b_h + I^c_h}{3}$ Objective function $\min(U_I)$ $U_I = \max\left\{U^1_I, U^2_I, U^3_I, ..., U^{h_{tot}}_I\right\}$ $U^h_I = \max\left\{I^a_{h_{\text{unbalance}}}, I^b_{h_{\text{unbalance}}}, I^c_{h_{\text{unbalance}}}\right\} h$ $'' h = 1, 2, ..., h_{\text{tot}}$ Where h is the every hour study period, CUI is the current unbalance index, loads or micro-FITs are X, Y, and Z, l and m are phase numbers (a, b, c), *i* is the bus number, N is the total number of system buses.
Remarks	Due to stochastic nature of solar based micro-FITs and loads, a mathematical model is utilized in order to be used for solving the phase balancing operational planning problem. Uses Genetics Algorithm.	
LFBM: Load Flow Balancing Method	Karim, et. al., (2015)	$P_i(t) = P_i k_{ui}(t)$ $k_{ui}(t) = [a_{i1}(t), a_{i2}(t), ..., a_{i24}(t)]$ where k_{ui}(t) is the utilization factor representing the position of the breaker. $a_{i1}(t)$ =0 implies breaker open whereas $a_{i1}(t)$ =1 for breaker close.

		$k_u(t)\cdot\sum_{i=1}^{k} P_i$; $k_u(t)\cdot\sum_{i=k+1}^{m} P_i$; $k_u(t)\cdot\sum_{i=m+1}^{n} P_i$ $\sum_{i=1}^{k} P_i\cdot k_{ui}(t)$; $\sum_{i=k+1}^{m} P_i\cdot k_{ui}(y)$; $\sum_{i=m+1}^{n} P_i\cdot K_{ui}(t)$ $\sum_{i=1}^{k} P_i(t)=\sum_{i=k+1}^{m} P_i(t)=\sum_{i=m+1}^{n} P_i(t)$ $\left\{\begin{array}{l}\sum_{i=1}^{k} P_i=\sum_{i=k+1}^{m} P_i=\sum_{i=m+1}^{n} P_i\\ \sum_{i=1}^{k} K_{ui}(t)=\sum_{i=k+1}^{m} k_{ui}(t)=\sum_{i=m+1}^{n} k_{ui}(t)\end{array}\right.$ where k is number of electrical loads on phase $N^0$1, m is the limits of electrical loads on phase $N^0$2 and n is the electrical loads number.
Remarks	To apply this new method, we must proceed like the following: • Gathering together into groups all electrical loads those have the same utilization factor k_{ui}(t) • Distribution all electrical loads between the three phases group by group. "L.F.B.M." that must be used before electrical installation. Its performance in one of the important stage that is technical study and electric wiring preparation.	

The Table1.3 shows the summarized techniques reported in the literature for phase balancing. Till date, the available phase balancing algorithms have considered rephasing either three-phase, two-phase, single-phase feeder laterals or single-phase CSMs at selected monitoring buses (like A, B1, B2 as in Fig. 1.4) alone in order to tackle the unbalancing issue while ignoring some of the other major unbalance influencing factors.

Table 1. 4 State of art methodology for phase balancing

Reference	Algorithm / method employed	Technique used	Rephasing elements	Load considered for rephasing	Rephasing element's phase
Zhu, et. al., (1998)	Mixed integer programming	Minimizing unbalance in branch currents	Feeder laterals	Individual customer load	1
Zhu, et. al., (1999)	Simulated annealing	Minimization of cost penalty function	Feeder laterals	Individual customer load	1
Gandomkar (2004), Chen and Cherng (1999)	Genetic algorithm	Minimization of power loss	Feeder laterals	Aggregate of load at bus	1
Lin, et. al., (2005), Lin, et. al., (2008)	Heuristic backtracking	Phase unbalance index	Feeder laterals	Aggregate of load at bus	3,2,1
Huang, et. al., (2008)	Immune algorithm	Neutral current reduction	Feeder laterals	Aggregate of load at bus	3,2,1
Hooshmand and Soltani (2012)	Bacterial forging by particle swarm optimization	Neutral current reduction	Feeder laterals	Aggregate of load at bus	3
Siti MW et. al (2007), Ukil and Siti (2008), Siti, et. al., (2009), Chitra and Neelaveni (2011)	Fuzzy logic	Average unbalance/phase	Customer service wire	Single load at each bus (Assumption)	1
Kuo and Chao (2010)	AM,FM,GIS*	Deviation in phase loading	Feeder laterals	Aggregate of load at bus	1
Sathiskumar and Thiruvenkadam (2011)	Hybrid greedy fuzzy	Voltage deviations	Feeder laterals	Aggregate of load at bus	2,1
Sathiskumar, et. al., (2012)	Self-adaptive hybrid differential evolution	Current deviations	Feeder laterals	Aggregate of load at bus	1
Khodr, et. al., (2006)	Neural networks	Current deviations	Service laterals	Single load at each bus	1
Siti, et. al., (2007)	-	Current deviations	Feeder laterals	Aggregate of load at bus	1
Haytham, et. al., (2014)	Genetics Algorithm	current unbalance index	single-phase loads/microFITs	single-phase loads and microFITs	1
Karim, et. al., (2015)	-	utilization factor	Customer service wire	Constant load (Assumption)	1

Consideration of such vital factors along with an aim to develop a simple mathematical formulation-based method is the motivation for this research work. On this line, to reduce the voltage drop, neutral current, line loss and number of phase moves an algorithm with the following characteristics is desirable:

- Can accommodate all types of CSMs (three-phase, two-phase and single-phase).
- Feeder laterals as movable in case of non-uniform feeder structure (two-phase and single-phase laterals).
- Time varying individual CSMs load profile, which is a feasible solution at present with the evolution of smart meters for LV consumers.
- Balancing of each candidate bus.

1.3 RESEARCH OBJECTIVES

This research work mainly deals with the development of phase balancing algorithm for single-phase, two-phase and three-phase feeder laterals as well as CSMs with an objective of line loss reduction and a minimum number of phase moves. The phase balancing algorithms are developed for the following:

1. Phase balancing of single-phase CSMs at each bus.
2. Phase balancing of three-phase and single-phase CSMs at each bus.
3. Phase balancing of three-phase and single-phase CSMs at each bus, by considering three-phase load as lumped load while balancing single-phase CSMs.
4. Phase balancing of single-phase CSMs at each bus using backward sweep technique.
5. Phase balancing of three-phase and single-phase CSMs at each bus using backward sweep technique.
6. Phase balancing of three-phase and single-phase CSMs at each bus using backward sweep technique by considering feeder laterals as movable.

7. To obtain most favourable phase balancing solution for a period of one day/ week/ month with a motive of providing maximum time interval between re-phasing tasks (such that number of times CSMs rephasing will be minimum in a day/week/month) and minimum number of rephasings.

Further, the performance of the above phase balancing algorithms are studied and verified using

- IEEE standard unbalanced distribution test feeders (13-bus and 123-bus), which provides the real time test environment for the most common features of distribution analysis
- The practical 16-bus LV distribution feeder with 113 consumers emanating from 100 kVA School TC Distribution transformer, Vinayakanagar, 11 kV Chandramouleswara feeder, Vijaynagar Sub Station, Mysuru for demonstration and validation.

1.4THESIS ORGANIZATION

The content of this thesis is divided into the following chapters.

Chapter 1 deals with the introduction to the topic covered in the thesis namely phase balancing technique. It also covers literature survey on this topic and the objectives so framed, in addition to the organization of the thesis at the end.

Chapter 2 covers the IEEE unbalanced test feeders and practical/live secondary distribution feeder considered for the proposed phase balancing algorithm analysis. Also, unbalanced radial distribution backward/forward sweep load flow is presented.

Chapter 3 focuses on the proposed phase balancing algorithms for unbalanced secondary distribution feeder. The selection of most favourable phase arrangement of CSMs is also discussed.

Chapter 4 is dedicated for the results and discussion of the proposed phase balancing algorithm. For unbalanced IEEE test feeders and practical/live secondary distribution feeder, the performance of the algorithm is compared for various conditions.

Chapter 5 covers the summary of the work carried out and briefly outlines the main contributions based on the investigations carried out. It also enlists the scope for future work.

CHAPTER 2

SECONDARY DISTRIBUTION SYSTEM AND UNBALANCED LOAD FLOW

This chapter comprises of unbalanced secondary distribution systems and load flow studies. The electrical system between the distribution substation (transmission end) and the consumer premises is called the Distribution system. This system is divided into two parts, the primary and secondary distribution systems. Primary Distribution includes everything between the distribution substation and the distribution transformers. Whereas, the secondary distribution starts from distribution transformer and ends at consumer meters. The secondary distribution network consists of feeder laterals and the service mains. Feeder lateral is a conductor between distribution transformer and consumer tapping point. A cable connecting the secondary feeder lateral to the consumer's meter point is termed as CSM.

In general, the primary distribution consumers are bulk in nature comprising of industries, hospitals, universities, companies, etc. and are of three-phase. These consumers are confined to have their overall load balanced at their supply end (i.e. utility meter) failing which leads to the additional surge charges. However, loading on secondary distribution system is not identical to that of the primary. They consist of LV three-phase and single-phase domestic and commercial consumers. These hybrid combinations of consumers are connected haphazardly, resulting in greater unbalance in the distribution feeder. Thus, it is the responsibility of the utility to maintain the system balance through the appropriate measures to supply reliable and efficient power. Wherein, the phase balancing approach is one of the efficient tools for tackling this issue.

2.1 FEEDERS CONSIDERED FOR THE STUDY

The most common features of distribution system exhibiting the real test environment is provided by the IEEE test feeders in specific 13-bus and 123-bus configuration (Dugan, 2017). In addition, to exemplify the effectiveness of the proposed algorithm, the practical LV distribution feeder with 16-buses and 113 consumers emanating from 100 kVA School TC Distribution transformer, Vinayakanagar, 11kV Chandramouleswara feeder, Vijaynagar Sub Station, Mysuru is considered along with IEEE test feeders.

2.1.1 IEEE 13-BUS TEST FEEDER

The IEEE 13-bus system (Refer Appendix I for system data) shown in Fig. 2.1 is an unbalanced distribution system with a base voltage of 4.16 kV. It has overhead lines, underground lines, voltage regulator and shunt capacitors. In this test system, voltage regulator and shunt capacitors are not considered for system, to study the effectiveness of phase balancing algorithm alone for unbalanced loads. The load data considered for the study are generated randomly (aggregate load at each bus is equal to the load data of IEEE 13-bus test feeder) as phase balancing needs individual CSMs load data at each bus is listed in Table 2.1.

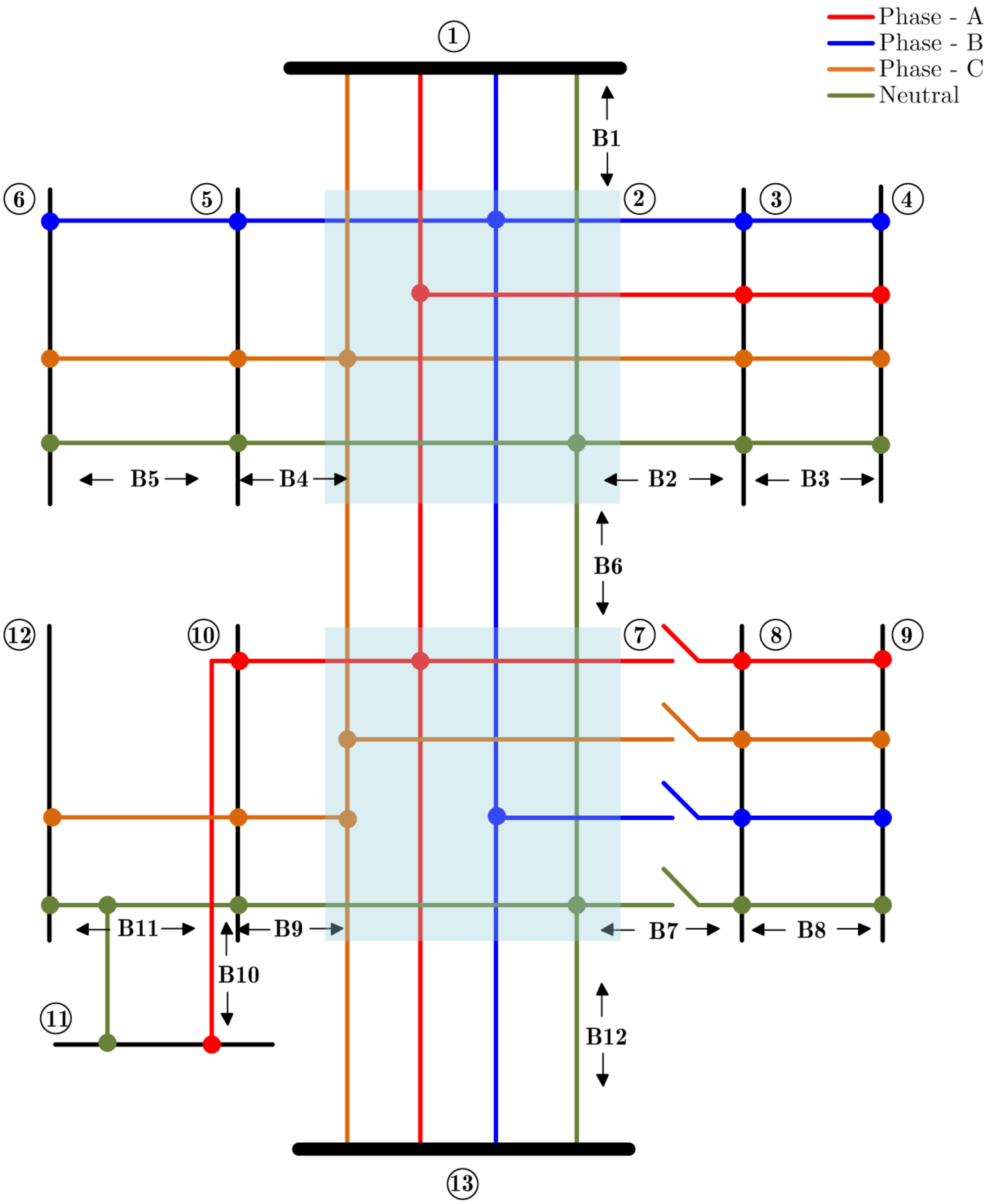


Figure 2. 1 Renumbered IEEE 13-bus test feeder (Dugan., 2017).

Table 2. 1 IEEE 13-bus test feeder Load Data

Spot Load							
		Phase A		Phase B		Phase C	
Bus		kW	kVAr	kW	kVAr	kW	kVAr
4		160	110	120	90	120	90
5		0	0	170	125	0	0
6		0	0	230	132	0	0
7		385	220	385	220	385	220
8		0	0	0	0	170	151
9		485	190	68	60	290	212
11		128	86	0	0	0	0
12		0	0	0	0	170	80
TOTAL		1158	606	973	627	1135	753
Distributed Load							
		Phase A		Phase B		Phase C	
Bus 1	Bus 2	kW	kVAr	kW	kVAr	kW	kVAr
2	7	17	10	66	38	117	68

2.1.2 IEEE 123-Bus Test Feeder

The IEEE 123-bus system is an unbalanced distribution system with base 4.16 kV as shown in Fig. 2.2. It has overhead lines, underground lines, voltage regulators, shunt capacitors and switches for alternate power flow. To exemplify the effectiveness of phase balancing algorithm solely the effect of both voltage regulators and shunt capacitors are not considered in the system. The load data considered for the study are generated randomly (aggregate load at each bus is equal to the load data of IEEE 123-bus test feeder) as phase balancing needs individual CSMs load data at each bus as listed in Table 2.2.

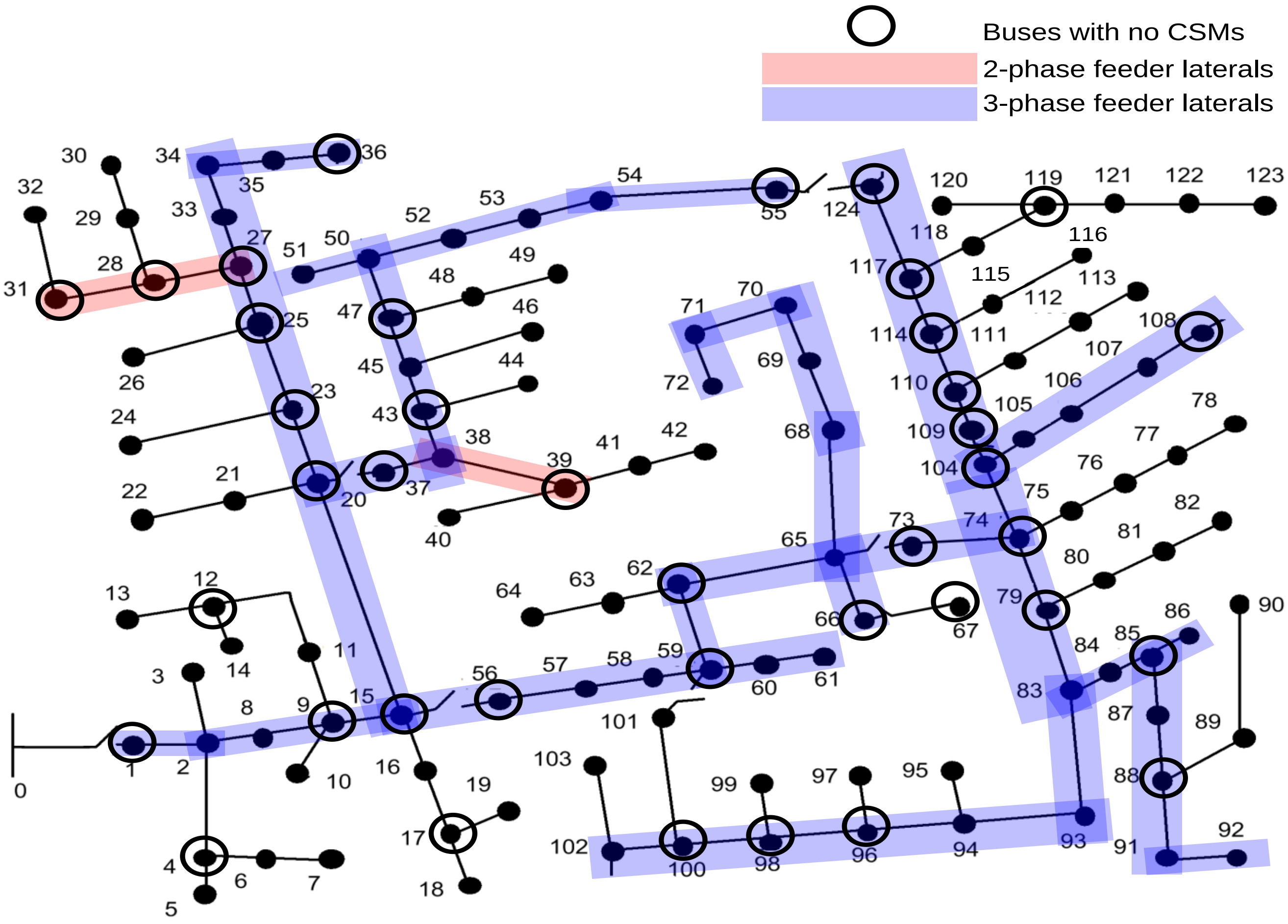


Figure 2. 2 Renumbered IEEE 123-bus Test Feeder (Dugan., 2017).

Table 2. 2 IEEE 123-bus test feeder Spot Load Data

New Bus	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-4
	Model	kW	kVAr	kW	kVAr	kW	kVAr
2	Y-PQ	40	20	0	0	0	0
3	Y-PQ	0	0	20	10	0	0
5	Y-PR	0	0	0	0	40	20
6	Y-I	0	0	0	0	20	10
7	Y-Z	0	0	0	0	40	20
8	Y-PQ	20	10	0	0	0	0
11	Y-PQ	40	20	0	0	0	0
14	Y-I	20	10	0	0	0	0
13	Y-Z	40	20	0	0	0	0
10	Y-PQ	0	0	20	10	0	0
18	Y-PQ	0	0	0	0	40	20
19	Y-PQ	0	0	0	0	20	10
21	Y-PQ	40	20	0	0	0	0
22	Y-I	40	20	0	0	0	0
24	Y-Z	0	0	40	20	0	0
26	Y-PQ	0	0	0	0	40	20
33	Y-I	40	20	0	0	0	0
34	Y-Z	40	20	0	0	0	0
35	Y-PQ	0	0	0	0	40	20
29	Y-PQ	0	0	0	0	20	10
30	Y-PQ	0	0	0	0	20	10
32	Y-I	40	20	0	0	0	0
16	Y-Z	0	0	0	0	40	20
38	D-PQ	40	20	0	0	0	0
40	Y-Z	40	20	0	0	0	0
41	Y-I	0	0	20	10	0	0
42	Y-PQ	0	0	20	10	0	0
44	Y-PQ	0	0	0	0	20	10
45	Y-PQ	20	10	0	0	0	0
46	Y-Z	0	0	40	20	0	0
48	Y-I	20	10	0	0	0	0
49	Y-PQ	20	10	0	0	0	0
50	Y-I	35	25	35	25	35	25
51	Y-Z	70	50	70	50	70	50
52	Y-PQ	35	25	70	50	35	20
53	Y-PQ	0	0	0	0	40	20
54	Y-PQ	20	10	0	0	0	0
57	Y-PQ	40	20	0	0	0	0
58	Y-PQ	40	20	0	0	0	0
60	Y-Z	20	10	0	0	0	0
61	Y-PQ	0	0	20	10	0	0
63	Y-I	0	0	20	10	0	0
64	Y-PQ	0	0	20	10	0	0
65	Y-PQ	20	10	0	0	0	0
68	Y-Z	0	0	0	0	40	20
69	Y-PQ	40	20	0	0	0	0
70	Y-I	0	0	75	35	0	0
71	D-Z	35	25	35	25	70	50
72	Y-PQ	0	0	0	0	75	35
75	Y-PQ	20	10	0	0	0	0
76	Y-PQ	40	20	0	0	0	0
77	Y-PQ	20	10	0	0	0	0
78	Y-PQ	40	20	0	0	0	0
80	Y-PQ	0	0	0	0	40	20
81	Y-Z	0	0	0	0	40	20
82	Y-PQ	0	0	0	0	40	20
83	D-I	105	80	70	50	70	50
84	Y-PQ	0	0	40	20	0	0
86	Y-Z	40	20	0	0	0	0
87	Y-PQ	0	0	40	20	0	0
91	Y-PQ	40	20	0	0	0	0
92	Y-PQ	0	0	0	0	20	10
89	Y-PQ	0	0	0	0	20	10
90	Y-PQ	0	0	0	0	40	20

New Bus	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-4
	Model	kW	kVAr	kW	kVAr	kW	kVAr
93	Y-PQ	0	0	20	10	0	0
94	Y-PQ	0	0	40	20	0	0
95	Y-PQ	40	20	0	0	0	0
97	Y-I	0	0	40	20	0	0
99	Y-PQ	0	0	0	0	40	20
101	Y-PQ	40	20	0	0	0	0
102	Y-PQ	0	0	20	10	0	0
103	Y-PQ	0	0	20	10	0	0
105	Y-PQ	40	20	0	0	0	0
106	Y-PQ	0	0	40	20	0	0
107	Y-Z	0	0	0	0	40	20
111	Y-PQ	0	0	0	0	20	10
112	Y-PQ	0	0	0	0	40	20
113	Y-PQ	0	0	0	0	40	20
115	Y-PQ	0	0	40	20	0	0
116	Y-PQ	0	0	40	20	0	0
118	Y-PQ	40	20	0	0	0	0
120	Y-PQ	20	10	0	0	0	0
121	Y-I	20	10	0	0	0	0
122	Y-Z	40	20	0	0	0	0
123	Y-PQ	20	10	0	0	0	0
Total		1420	775	915	515	1155	630

2.1.3 Real Time Secondary Distribution Feeder

The 16-bus LV distribution feeder emanating from 100 kVA School TC Distribution Transformer, Vinayakanagar, 11 kV Chandramouleswara Feeder, Vijaynagar Substation, Mysuru considered for the study is shown in Fig.2.3. It consists of 113 single-phase CSMs and the real time data corresponding to the month of February 2017 is employed for validating the developed algorithms. A sample data corresponding to 19th Feb 2017 is enlisted in Appendix II. Feeder configuration is tabulated in Table 2.3, and its consumer mapping is listed in Table 2.4

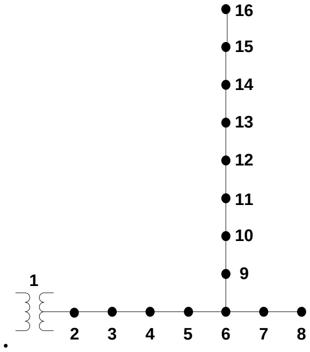


Figure 2. 3 16-bus LV typical system of Mysuru

Table 2. 3 Feeder configuration of 16-bus LV typical system of Mysuru

Sl.No	Bus1	Bus2	Length(m)
1	1	2	9
2	2	3	2
3	3	4	25
4	4	5	40
5	5	6	20
6	6	7	50
7	7	8	15
8	8	9	1
9	9	10	30
10	10	11	25
11	11	12	20
12	12	13	20
13	13	14	30
14	14	15	50
15	15	16	20

Table 2. 4 Consumer Mapping of 16-bus LV typical system of Mysuru

Sl.No	Phase(R/Y/B)	Pole	Consumer
1	B	5	2
2	B	5	3
3	B	5	4
4	Y	6	5
5	Y	6	6
6	Y	6	7
7	Y	6	8
8	Y	6	9
9	B	6	10
10	R	8	11
11	R	8	12
12	R	8	13
13	R	8	14
14	R	8	15
15	R	8	16
16	R	8	17
17	R	8	18
18	R	8	19
19	Y	8	20
20	Y	8	21
21	Y	8	22
22	Y	8	23
23	Y	8	24
24	Y	8	25
25	Y	8	26
26	Y	8	27
27	Y	8	28
28	Y	8	29
29	Y	8	30
30	B	8	31
31	B	8	32
32	B	8	33
33	R	10	34
34	R	10	35

Sl.No	Phase(R/Y/B)	Pole	Consumer
35	R	10	36
36	R	10	37
37	R	10	38
38	R	10	39
39	R	10	40
40	R	10	41
41	R	10	45
42	R	10	46
43	Y	11	48
44	Y	11	49
45	Y	1	50
46	Y	11	51
47	Y	11	52
48	Y	11	53
49	Y	11	54
50	Y	11	55
51	Y	11	56
52	Y	11	57
53	Y	11	58
54	Y	11	59
55	Y	11	60
56	Y	11	61
57	Y	11	62
58	Y	11	63
59	Y	11	64
60	Y	12	65
61	Y	12	66
62	Y	12	67
63	Y	12	68
64	R	14	69
65	R	14	70
66	R	14	71
67	R	14	72
68	R	14	73
69	R	14	74
70	Y	14	75
71	Y	14	76

Sl.No	Phase(R/Y/B)	Pole	Consumer
72	Y	14	77
73	Y	14	78
74	Y	14	79
75	Y	14	80
76	B	14	81
77	B	14	82
78	B	14	83
79	B	14	84
80	B	15	85
81	B	15	86
82	B	15	87
83	B	15	88
84	B	15	89
85	B	15	90
86	B	15	91
87	B	15	92
88	B	15	93
89	B	15	94
90	B	15	95
91	B	15	96
92	B	15	97
93	B	15	98
94	Y	16	99
95	Y	16	100
96	Y	16	101
97	Y	16	102
98	Y	16	104
99	Y	16	105
100	Y	16	106
101	Y	16	107
102	Y	16	108
103	Y	16	109
104	Y	16	110
105	Y	16	111
106	Y	16	112
107	Y	16	113

The conductor used for the LV feeder is ACSR 6/1 rabbit conductor. The specifications of the conductor are diameter 0.398 inches, GMR (Geometrical Mean radius) is 0.00446 feet, resistance (r_i) is 1.12 ohms/mile, capacity is 230 Amps, size is 1/10, frequency (f) is 50 Hz, and earth resistivity (ρ) is 100 ohm-meters. The line Impedance and admittances are computed using following equations:

$$z_{ii} = r_i + 0.00158836 \cdot f + j0.00202237 \cdot f \left(\ln \frac{1}{\mathrm{GMR}_i} + 7.6786 + \frac{1}{2} \ln \frac{\rho}{f} \right)$$

$$z_{ij} = 0.00158836 \cdot f + j0.00202237 \cdot f \left(\ln \frac{1}{\mathrm{D}_{ij}} + 7.6786 + \frac{1}{2} \ln \frac{\rho}{f} \right)$$

$$y_{ii} = 11.17689 \cdot \ln \frac{S_{ii}}{RD_{ii}} \quad \text{mile/}\mu\text{F}$$

$$y_{ij} = 11.17689 \cdot \ln \frac{S_{ij}}{D_{ij}} \quad \text{mile/}\mu\text{F}$$

where

z_{ii} is the self impedance of the conductor in ohms/mile

z_{ij} is the mutual impedance between conductors i and j in ohms/mile

y_{ii} is the self admittance

y_{ij} is the mutual admittance

2.1 LOAD FLOWS

Ever since its inception, the load flow analysis is an important and fundamental tool in the power system studies. Given radial structure, multiphase, high R/X ratio, unbalanced loading and a higher number of lines in the distribution system as compared to transmission system, application of traditional load flows remains unsuitable. Therefore, many approaches for distribution system load flow analysis are proposed in the recent past. Among these, the backward-forward sweep load flow method is prevalently used for radial distribution system, same has been considered for the further system analysis

(S.Mishra, et. al., 2012). Here, for a fast implementation of backward-forward sweep based load flow, following arrays are used for the bus identification. The IEEE 13-bus test feeder is considered for the demonstration of bus identification process. The vector abd[s] stores adjacent buses of each bus of the feeder as given in Table 2.5. Vectors mf[i] and mt[i] specified in Table2.6 are the pointers to the abd[s] vector and stores the starting and end memory location of bus i of the abd[s] vector.

Table 2. 5 Adjacent buses of each bus

Sl.No/s	Bus	abd(s)
1	1	2
2	2	1
3		3
4		5
5		7
6	3	2
7		4
8	4	3
9	5	2
10		6
11	6	5
12	7	2
13		8
14		10
15		13
16	8	7
17		9
18	9	8
19	10	7
20		11
21		12
22	11	10
23	12	10
24	13	7

Table 2. 6 Starting and end memory location of the each bus

Bus No/i	mf(i)	mt(i)
1	1	1
2	2	5
3	6	7
4	8	8
5	9	10
6	11	11
7	12	15
8	16	17
9	18	18
10	19	21
11	22	22
12	23	23
13	24	24

The configuration codes of the IEEE 13-bus feeder are listed in Table 2.7. Two vectors bp[i] and bt[i] of the Table 2.8 stores the bus phase nature and assigned bus configuration.

Table 2. 7 Branch Configuration

Configuration	Phasing	Spacing
1	BACN	500
2	CABN	500
3	CBN	505
4	ACN	505
5	CN	510
6	ABCN	515
7	AN	520

Table 2. 8 Bus type and its configuration

Bus No/i (preceding branch)	bp(i)	bt(i)
2	3	1
3	3	2
4	Regulator	2
5	2	3
6	2	3
7	3	1
8	Switch	6
9	3	6
10	2	4
11	1	7
12	1	5
13	3	1

Listed below summarizes the steps of the backward-forward sweep load flow with appropriate equations for an unbalanced distribution network.

1. Read the unbalanced distribution network data.
2. Compute vectors mf[i], mt[i], abd[i], bp[i] and bt[i] for bus identification.
3. Initialize the voltage magnitude as 1p.u and voltage angles 0, -120 and 120 for phases A, B and C at each bus.
4. Initialize the iteration count k=1
5. Calculate current at all buses using following equations, the bp[i] and bt[i] values of the bus are to ensure the existing of concerned phases.

$$I_{ia} = \left(\frac{P_{ia} + jQ_{ia}}{V_{ia}} \right)^* - Y_{ia} V_{ia}$$

$$I_{ib} = \left(\frac{P_{ib} + jQ_{ib}}{V_{ib}} \right)^{*} - Y_{ib} V_{ib}$$

$$I_{ic} = \left(\frac{P_{ic} + jQ_{ic}}{V_{ic}} \right)^{*} - Y_{ic} V_{ic}$$

6. Calculate the branch current in the backward sweep, check mt[i]-mf[i]
    - if zero, it is an end bus, branch current equal to the node current
    - if not zero, it is an intermediate or junction bus where branch current is the sum of node current and preceding buses branch current.
7. Calculate the node voltage in forward sweep using following equation based on bp[i] and bt[i] values of the bus.

For three-phase feeder lateral

$$\begin{bmatrix} V_{ia} \\ V_{ib} \\ V_{ic} \end{bmatrix} = \begin{bmatrix} V_{ja} \\ V_{jb} \\ V_{jc} \end{bmatrix} + \begin{bmatrix} Z_{aa-n} & Z_{ab-n} & Z_{ac-n} \\ Z_{ba-n} & Z_{bb-n} & Z_{bc-n} \\ Z_{ca-n} & Z_{cb-n} & Z_{cc-n} \end{bmatrix} \begin{bmatrix} I_{ija} \\ I_{ijb} \\ I_{ijc} \end{bmatrix}$$

For two-phase feeder lateral

$$\begin{bmatrix} V_{ia} \\ V_{ib} \end{bmatrix} = \begin{bmatrix} V_{ja} \\ V_{jb} \end{bmatrix} + \begin{bmatrix} Z_{aa-n} & Z_{ab-n} \\ Z_{ba-n} & Z_{bb-n} \end{bmatrix} \begin{bmatrix} I_{ija} \\ I_{ijb} \end{bmatrix}$$

$$\begin{bmatrix} V_{ib} \\ V_{ic} \end{bmatrix} = \begin{bmatrix} V_{jb} \\ V_{jc} \end{bmatrix} + \begin{bmatrix} Z_{bb-n} & Z_{bc-n} \\ Z_{cb-n} & Z_{cc-n} \end{bmatrix} \begin{bmatrix} I_{ijb} \\ I_{ijc} \end{bmatrix}$$

$$\begin{bmatrix} V_{ia} \\ V_{ic} \end{bmatrix} = \begin{bmatrix} V_{ja} \\ V_{jc} \end{bmatrix} + \begin{bmatrix} Z_{aa-n} & Z_{ac-n} \\ Z_{ca-n} & Z_{cc-n} \end{bmatrix} \begin{bmatrix} I_{ija} \\ I_{ijc} \end{bmatrix}$$

For 1Phase feeder lateral

$$V_{ia} = V_{ja} + Z_{aa-n} \times I_{ija}$$
$$V_{ib} = V_{jb} + Z_{bb-n} \times I_{ijb}$$
$$V_{ic} = V_{jc} + Z_{cc-n} \times I_{ijc}$$

Here preceding bus is obtained using

```
for k=mf[i]:mt[i]
if abd[k]<i
n=abd[k]
```

8. Check for convergence with respect to voltage magnitude. If not, go to step 5.
9. Calculate power flows and loss.

This backward-forward sweep load flow is the tool applied in common to all feeders considered for the study.

CHAPTER 3

PROPOSED PHASE BALANCING ALGORITHM

In the previous chapter, the basics of the distribution system and the feeders considered for the study were presented. Also, the unbalanced backward-forward sweep load flow for the secondary distribution network was discussed. Here we propose a phase balancing algorithm for the secondary distribution network capable of balancing the unbalanced network by catering each bus.

Secondary distribution network phase balancing algorithm is developed by considering all types of CSMs (three-phase, two-phase and single-phase) and movable feeder laterals (two-phase and single-phase) by taking into the account of time varying individual CSM load profile at each bus. This technique is feasible with the evolution of smart meters for LV consumers, which is the input for the proposed algorithm. The objectives of the proposed algorithm are to accomplish CSMs rearrangement, line loss reduction, diminution of neutral current, enhanced voltage profile and a minimum number of rephasings. It comprises of simple mathematical parameters such as average load per phase and average load per service main.

The time varying nature of consumer load requires continuous monitoring and rephasing of CSM to keep the network balanced thereby affecting the power system reliability. Since, utilities cannot afford many phase moves and balance corrections for time varying loads, as it results in more power interruptions. Thus, the selection of a rephasing arrangement which results in minimum number of CSM phase change over is essential. A method is developed for the selection of most favourable CSMs arrangement over a period (day or week or month) with a sole objective to minimize the number of CSM rephasings and power interruptions.

3.1 PROPOSED PHASE BALANCING ALGORITHMS

The proposed phase balancing algorithm technique is discussed for balancing (a) single-phase CSMs alone, (b) three-phase and single-phase CSMs, (c) three-phase and single-phase CSMs by considering three-phase load as lumped load while balancing single-phase CSMs, (d) single-phase CSMs alone using backward sweep technique, (e) three-phase and single-phase CSMs using backward sweep technique, (f) three-phase and single-phase CSMs using backward sweep technique by considering feeder laterals as movable at each bus respectively with an objective of line loss reduction, minimum number of phase moves, branch current and neutral current reduction and enhanced voltage profile.

3.1.1 Phase Balancing Methodology

Phase balancing techniques reported in the literature uses optimization techniques (based on the random generation of combinations and iterative process) to obtain most favourable phase arrangement of CSM. Here, the balancing is with respect to transformer secondary terminal/ selected buses like A, B1, B2 as in Fig. 1.4 which results in more number of CSMs (since it includes service at that particular bus and its succeeding buses). Whereas, the proposed algorithm as shown in Fig 3.1 uses simple mathematical terms such as average load per phase, average load per CSM and possible combinations of required number of CSMs to be rephased to obtain the rephasing arrangement of single-phase and three-phase CSM at each bus. These parameters are sufficient to obtain the rephasing arrangement of CSM at each bus as the numbers of CSM will be very few when each bus is considered. In addition, phase sequence is one among the prominent parameters considered while rephasing three-phase CSM. For instance, a three-phase CSM with ABC sequence has to be rephased to either BCA or CAB sequences. Single-phase CSM can be rephased to any one of the other two phases.

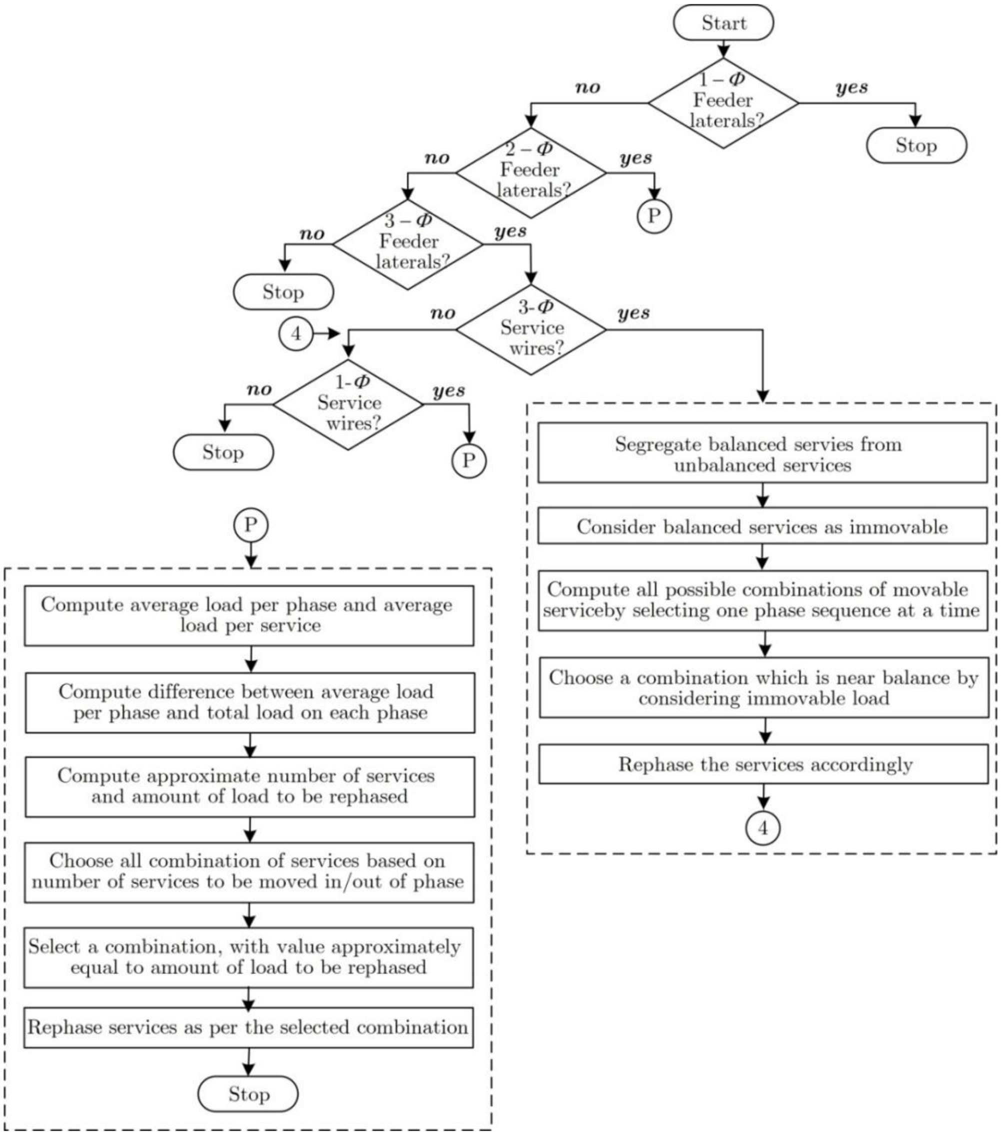


Figure 3. 1 Proposed phase balancing algorithm flowchart

For the bus having three phase feeder lateral, initially the three-phase CSM's undergo load balancing following which the single phase CSM's are balanced as described below.

In the case of three-phase CSMs, algorithm as shown in Fig. 3.2, initially segregates the balanced CSMs from an unbalanced CSMs. Segregated balanced CSMs act as immovable whereas, other CSMs are movable. Then, all possible combinations of movable services are computed by selecting one phase sequence at a time among ABC, BCA and CAB. Finally, one of the combinations resulting in near balance by considering immovable CSMs load is selected. As per the selected combination, respective CSMs are to be rephased.

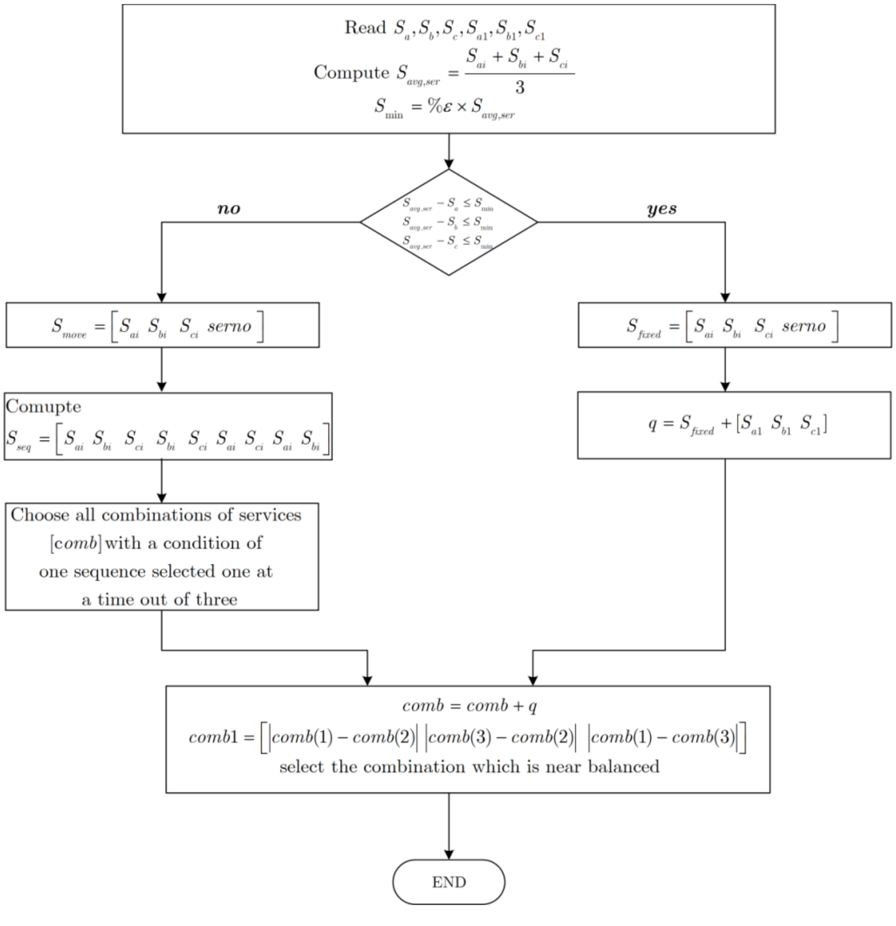


Figure 3. 2 Proposed three-phase CSMs phase balancing algorithm flowchart

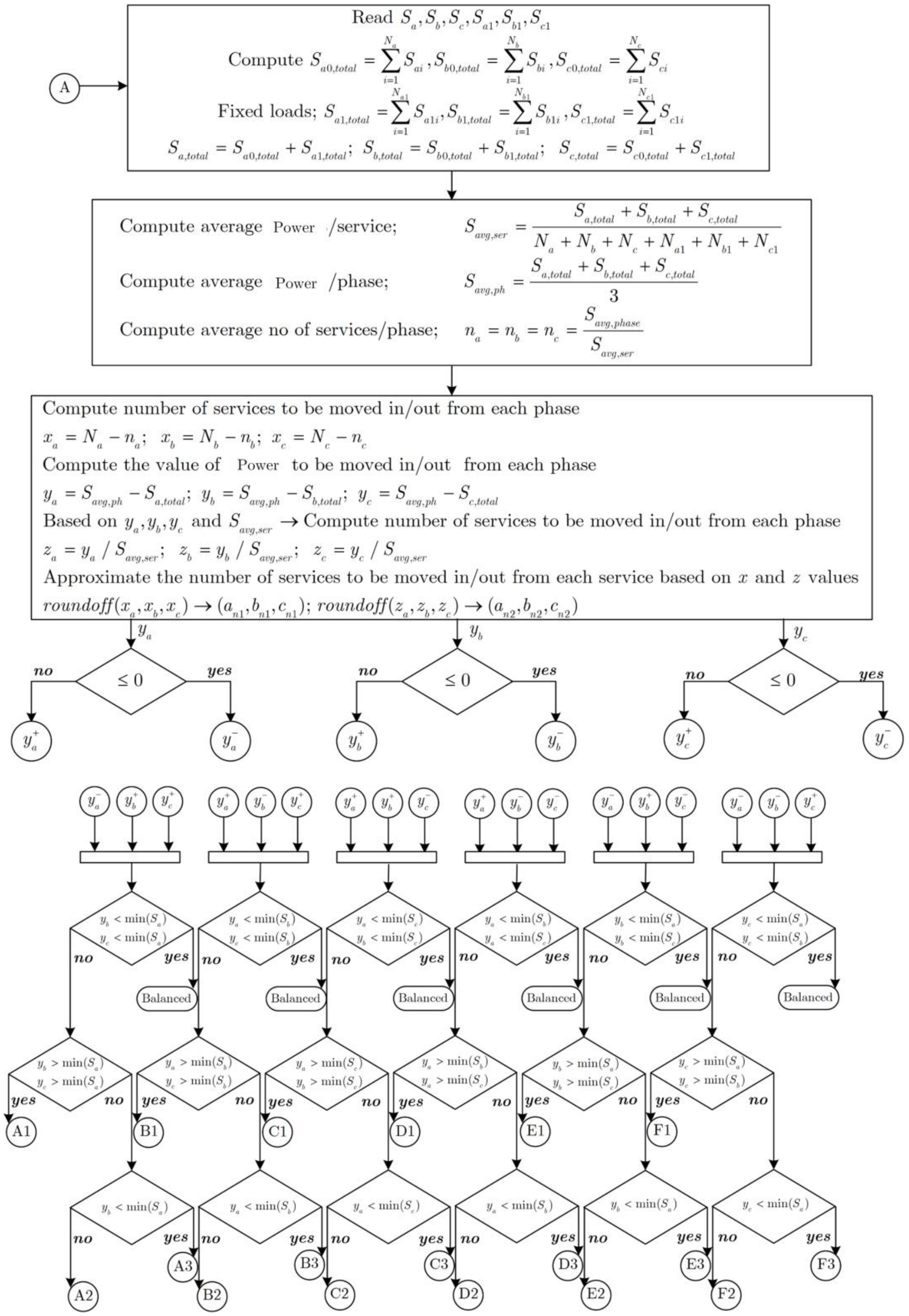


Figure 3. 3 Proposed single-phase CSMs phase balancing algorithm flowchart

For single-phase CSMs, average load per phase and average load per CSM are computed. The approximate number of CSMs to move in/ out are estimated based on the computed values. In continuation, the amount of load to be moved in/out of the phase is the difference between the existing load on phase and average load per phase by considering already balanced three-phase CSMs load as immovable. Secondly, all the possible combinations of CSMs are computed for the obtained number of CSMs to move in/out. Finally, the combination of CSMs whose sum is approximately equal to the amount of load to move in/out is selected. As per the selected combination, respective CSMs are to be rephased. The same is shown in Fig. 3.3 and Fig. 3.4 respectively. Case A of Fig. 3.3 is presented in Fig. 3.4 and is similar to other cases from B to F.

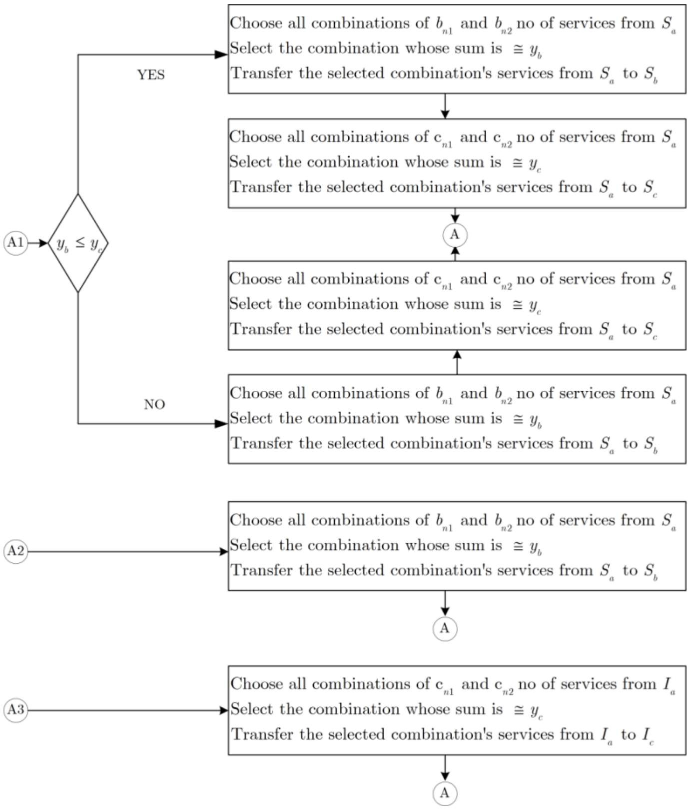


Figure 3. 4 Continuation of proposed single-phase CSMs phase balancing algorithm flowchart

For the bus having two-phase feeder lateral, existing load is balanced among the two phases similar to single-phase CSMs balancing among three phases as shown in Fig. 3.5.

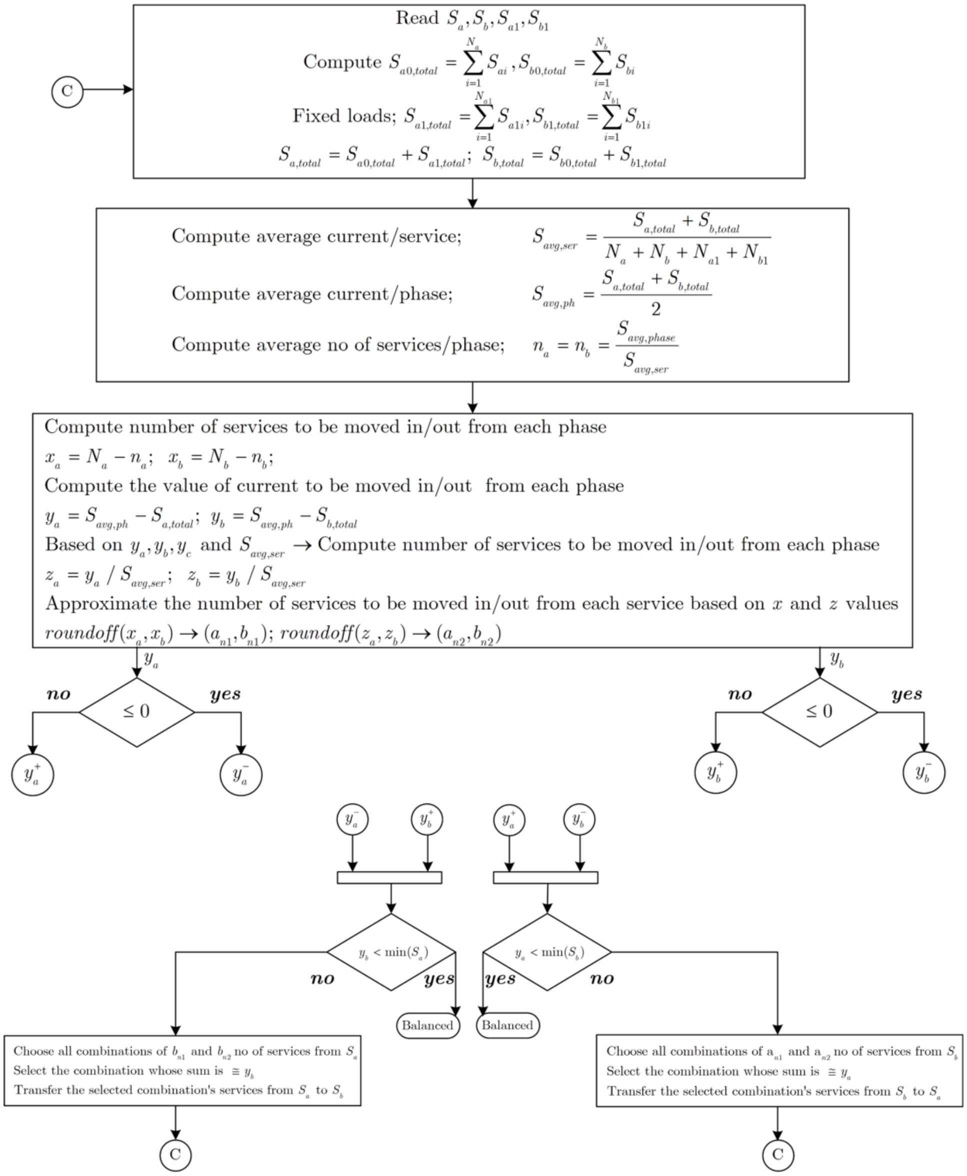


Figure 3. 5 Proposed two-phase feeder laterals phase balancing algorithm flowchart for the bus having single-phase feeder lateral, existing load is considered as lumped load at preceding bus.

Further, backward sweep technique based phase balancing algorithm is developed. It balances each bus from tail end to the feeder origination. The loads on the rephased buses are considered as lumped/immovable while balancing the preceding bus. This process is repeated such that the network after the bus is balanced (as viewed from the bus being balanced) which in turn resulting in an effective reduction of neutral current and branch currents.

3.1.2 Algorithm 1: Phase Balancing of Single-Phase CSMs at Each Bus

In the existing literature, there is only mention of single-phase CSMs phase balancing at particular selected bus. However in this work, balancing at each bus is considered in order to treat the instigation of the unbalance problem at its root level. Phase balancing at each bus from tail end to the origin of the feeder results in whole feeder balance thereby reducing all branch currents and neutral current. The process of phase balancing from tail end to the origin of the feeder is explained below by considering IEEE 13-bus test feeder.

- As the load at bus 13 is absent, it does not require phase balancing.
- Since the branches 12-10 and 11-10 are single-phase feeder laterals, bus 11 and 12 does not require phase balancing.
- Since bus 9 is of three-phase nature, the single-phase CSMs are rephased resulting in balanced load on three phases.
- Bus 8 is of three-phase nature, consisting of only single-phase CSMs on phase C. Thus a few CSMs on phase C are transferred to phase A and B.
- Phase balancing at bus 7 is accomplished in the same manner as that of bus 9.
- Bus 6 is of two-phase nature, consisting of CSMs on phase B alone. While transferring a few loads on phase B to phase C, bus 6 is balanced.
- Phase balancing at bus 5 is accomplished in the same manner as that of bus 6.

- Phase balancing at bus 4 and bus 2 is accomplished in the same manner as that of bus 9.

3.1.3 Algorithm 2: Phase Balancing of Three-Phase and Single-Phase CSMs at Each Bus

In this case, the three-phase CSMs are considered along with the single-phase CSMs for balancing the feeder since this approach is an unattended issue in the literature. The process of phase balancing from tail end to the origin of the feeder is explained below by considering IEEE 13-bus test feeder.

- As the load at bus 13 is absent, it does not require phase balancing.
- Since the branches 12-10 and 11-10 are single-phase feeder laterals, bus 11 and 12 does not require phase balancing.
- Bus 9 is of three-phase nature, having both three-phase and single-phase CSMs which are balanced independently and irrespective of each other loads.
- Bus 8 is of three-phase nature, consisting of only single-phase CSMs on phase C. Thus a few CSMs on phase C are transferred to phase A and B.
- Phase balancing at bus 7 is accomplished in the same manner as that of bus 9.
- Bus 6 is of two-phase nature, consisting of CSMs on phase B alone. While transferring a few loads on phase B to phase C, bus 6 is balanced.
- Phase balancing at bus 5 is accomplished in the same manner as that of bus 6.
- Phase balancing at bus 4 and bus 2 is accomplished in the same manner as that of bus 9.

3.1.4 Algorithm 3: Phase Balancing of Three-Phase and Single-Phase CSMs at Each Bus, by Considering Three-Phase CSMs Load as Lumped Load while Balancing Single-Phase CSMs

In this case, firstly, the three-phase CSMs are balanced. Secondly, the single-phase CSMs are balanced by considering three-phase CSMs load as lumped at each bus. The process of phase balancing is explained below by considering IEEE 13-bus test feeder.

- As the load at bus 13 is absent, it does not require phase balancing.
- Since the branches 12-10 and 11-10 are single-phase feeder laterals, bus 11 and 12 does not require phase balancing.
- Bus 9 is of three-phase nature, having both three-phase and single-phase CSMs. Following the balancing of three-phase CSMs, the single-phase CSMs are balanced by assuming three-phase consumers load as lumped load.
- Bus 8 is of three-phase nature, consisting of only single-phase CSMs on phase C. Thus a few CSMs on phase C are transferred to phase A and B.
- Phase balancing at bus 7 is accomplished in the same manner as that of bus 9.
- Bus 6 is of two-phase nature, consisting of CSMs on phase B alone. While transferring a few loads on phase B to phase C, bus 6 is balanced.
- Phase balancing at bus 5 is accomplished in the same manner as that of bus 6.
- Phase balancing at bus 4 and bus 2 is accomplished in the same manner as that of bus 9.

3.1.5 Algorithm 4: Phase Balancing of Single-Phase CSMs using Backward Sweep Technique

In this case, single-phase CSMs are balanced at each bus using backward sweep technique from tail end to the feeder origination. In backward sweep, the load on the rephased bus is considered as a lumped/immovable load at the next monitoring bus. The process of phase balancing is explained below by considering IEEE 13-bus test feeder.

- As the load at bus 13 is absent, it does not require phase balancing.
- Since the branches 12-10 and 11-10 are single-phase feeder laterals, bus 11 and 12 does not require phase balancing.
- Bus 9 is of three-phase nature and tail end bus, having both three-phase and single-phase CSMs. Balancing of single-phase CSMs is carried out by assuming three-phase consumers load as lumped load irrespective of its balance status.
- Bus 8 is of three-phase nature and intermediate bus, consisting of only single-phase CSMs on phase C. Thus a few CSMs on phase C are transferred to phase A and B by accounting load at bus 9 as lumped.
- Bus 7 is of three-phase nature and junction bus, having both three-phase and single-phase CSMs. Balancing of single-phase CSMs is carried out by assuming its own three-phase consumers load and loads at bus 12,11, 9, 8 as lumped.
- Bus 6 is of two-phase nature, consisting of CSMs on phase B alone. While transferring a few loads on phase B to phase C, bus 6 is balanced.
- Phase balancing at bus 5 is accomplished in the same manner as that of bus 6 by considering the load at bus 6 as lumped.
- Balancing at bus 4 is accomplished in the similar way as that of bus 9. The load on bus 4 is reflected as lumped load on bus 3 and thus bus 3 does not require balancing since it has no CSMs.

- Bus 2 is of three-phase nature and junction bus, having both three-phase and single-phase CSMs. Balancing of single-phase CSMs is carried out by assuming its own three-phase consumers load and loads at bus 12, 11, 9, 8, 7, 6, 5, 4 and 3 as lumped.

3.1.6 Algorithm 5: Phase Balancing of Three-Phase and Single-Phase CSMs at Each Bus using Backward Sweep Technique

In this case, both three-phase and single-phase CSMs are balanced at each bus using backward sweep technique. The process of phase balancing is explained below by considering IEEE 13-bus test feeder.

- As the load at bus 13 is absent, it does not require phase balancing.
- Since the branches 12-10 and 11-10 are single-phase feeder laterals, bus 11 and 12 does not require phase balancing.
- Bus 9 is of three-phase nature and tail end bus, having both three-phase and single-phase CSMs. Following the balancing of three-phase CSMs, the single-phase CSMs are balanced by assuming three-phase consumers load as lumped load.
- Bus 8 is of three-phase nature and intermediate bus, consisting of only single-phase CSMs on phase C. Thus a few CSMs on phase C are transferred to phase A and B by accounting load at bus 9 as lumped.
- Bus 7 is of three-phase nature and junction bus, having both three-phase and single-phase CSMs. Firstly the three-phase CSMs are to be balanced by considering loads at bus 12, 11, 9 and 8 as lumped. Secondly, the single-phase CSMs are balanced by assuming the formerly balanced three-phase CSM load and loads at bus 12, 11, 9 and 8 as lumped.

- Bus 6 is of two-phase nature, consisting of CSMs on phase B alone. While transferring a few loads on phase B to phase C, bus 6 is balanced.
- Phase balancing at bus 5 is accomplished in the same manner as that of bus 6 by considering the load at bus 6 as lumped.
- Balancing at bus 4 is accomplished in the similar way as that of bus 9. The load on bus 4 is reflected as lumped load on bus 3 and thus bus 3 does not require balancing since it has no CSMs.
- Bus 2 is of three-phase nature and junction bus, having both three-phase and single-phase CSMs. Firstly the three-phase CSMs are to be balanced by considering loads at bus 12, 11, 9, 8, 7, 6, 5, 4 and 3 as lumped. Secondly, the single-phase CSMs are balanced by assuming the formerly balanced three-phase CSM load and loads at bus 12, 11, 9, 8, 7, 6, 5, 4 and 3 as lumped.

3.1.7 Algorithm 6: Phase Balancing of Three-Phase and Single-Phase CSMs at Each Bus using Backward Sweep Technique by Considering Feeder Laterals as Movable

In this case, both three-phase and single-phase CSMs are balanced at each bus using backward sweep technique by considering single-phase and two-phase feeder laterals as movable. The process of phase balancing is explained below by considering IEEE 13-bus test feeder.

- As the load at bus 13 is absent, it does not require phase balancing.
- Since the branches 12-10 and 11-10 are single-phase feeder laterals, bus 11 and 12 does not require phase balancing.
- Bus 9 is of three-phase nature and tail end bus, having both three-phase and single-phase CSMs. Following the balancing of three-phase CSMs, the single-

phase CSMs are balanced by assuming three-phase consumers load as lumped load.

- Bus 8 is of three-phase nature and intermediate bus, consisting of only single-phase CSMs on phase C. Thus a few CSMs on phase C are transferred to phase A and B by accounting load at bus 9 as lumped.
- Bus 7 is of three-phase nature and junction bus, having both three-phase and single-phase CSMs. Firstly the three-phase CSMs are to be balanced by considering load at bus 9 and 8 as lumped. Secondly, single-phase CSMs are balanced; by considering the load at bus 10 (i.e bus 12 and 11 load) as movable, formerly balanced three-phase CSM load at bus 7 and consolidated load at bus 9 and 8 as lumped.
- Bus 6 is of two-phase nature consisting of CSMs on phase B alone. While transferring a few loads on phase B to phase C, bus 6 is balanced.
- Phase balancing at bus 5 is accomplished in the same manner as that of bus 6 by considering the load at bus 6 as lumped.
- Balancing at bus 4 is accomplished in the similar way as that of bus 9. The load on bus 4 is reflected as lumped load on bus 3 and thus bus 3 does not require balancing since it has no CSMs.
- Bus 2 is of three-phase nature and junction bus, having both three-phase and single-phase CSMs. Firstly, the three-phase CSMs are to be balanced by considering loads of bus 12, 11, 9, 8, 7, 4 and 3 as lumped. Secondly, single-phase CSMs are balanced; by considering the load at bus 5 (with the inclusion of bus 5 load) as movable, formerly balanced three-phase CSM load at bus 2, consolidated loads at bus 12, 11, 9, 8, 7, 4 and 3 as lumped.

3.2 SELECTION OF MOST FAVOURABLE PHASE ARRANGEMENT of CSMs

The time varying nature of load requires continuous monitoring and rephasings of the CSMs to keep the system balanced. However, this affects the reliability of the power system due to regular interruptions caused by phase rephasing due to change in the load. Thus, selection of a rephasing arrangement that results in minimum number of changeover of CSMs from one phase to other phase is essential. The corresponding flow diagram is shown in Fig. 3.6.

To demonstrate the selection of most favourable phase arrangement, four different load profiles are considered with the sampling interval of 6 hours in a day. Input 1, Input 2, Input 3 and Input 4 are the load profiles at time intervals T1, T2, T3, and T4 respectively. A1, A2, A3 and A4 are the corresponding CSMs phase arrangement obtained with the application of phase balancing algorithm to Input1, Input2, Input3 and Input4 respectively as shown in Fig 3.7.

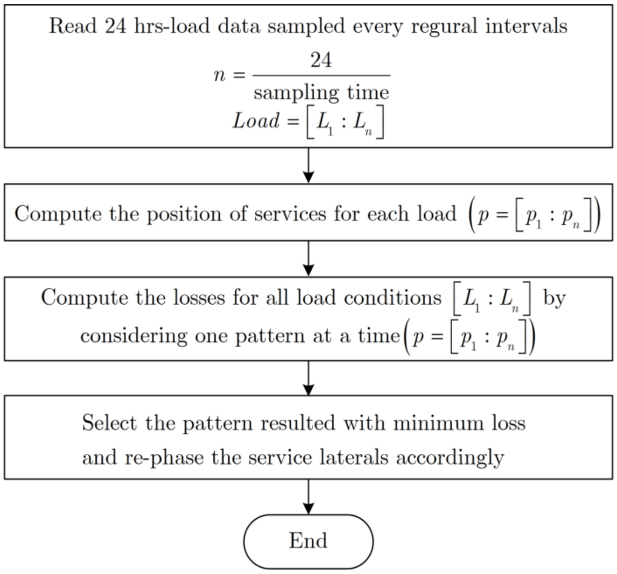


Figure 3. 6 Flow chart for selection of most favourable CSMs phase arrangement

	T1	T2	T3	T4
Input1	A1			
Input2		A2		
Input3			A3	
Input4				A4

Figure 3. 7 Phase arrangements corresponding to its input and time interval

For 24 hours {T1: T4}, rephasing of CSMs has to be carried out four times, which is not reliable. Table 3.1 is computed to select the most favourable CSMs phase arrangement amongst A1, A2, A3 and A4 selection which results in minimum line loss per day. Line losses are estimated for four sets of load data {lnput1:lnput4} and their respective balanced CSM phase arrangements {A1: A4} are tabulated in Table 3.1. The phase arrangement resulting in minimum line loss and requiring less number of rephasings for all the four load data is chosen as the most favourable CSMs phase arrangement over the interval {T1: T4}.

Table 3. 1 Loss corresponding to input and phase arrangement

	A1	A2	A3	A4
Input1	Loss11	Loss12	Loss13	Loss14
Input2	Loss21	Loss22	Loss23	Loss24
Input3	Loss31	Loss32	Loss33	Loss34
Input4	Loss41	Loss42	Loss43	Loss44

The logic behind the selection of most favourable CSMs phase arrangement is mathematically expressed as follows

L(A)=Loss11+Loss22+Loss33+Loss44 (Most Minimum Loss)

L(A1)=Loss11+Loss21+Loss31+Loss41; L(A2)=Loss12+Loss22+Loss32+Loss42;

L(A3)=Loss13+Loss23+Loss33+Loss43; L(A4)=Loss14+Loss24+Loss34+Loss44;

With the application of the selected most favourable phase arrangement, the number of times of CSM rephasing and power interruptions is minimized.

CHAPTER 4

RESULTS AND DISCUSSION

The algorithms for phase balancing are developed in MATLAB considering the following vivid cases which includes (a) single-phase CSM alone, (b) three-phase and single-phase CSM, (c) three-phase and single-phase CSM by considering three-phase load as lumped load while balancing single-phase CSM, (d) single-phase CSM alone using backward sweep technique, (e) three-phase and single-phase CSM using backward sweep technique, (f) three-phase and single-phase CSM using backward sweep technique by considering feeder laterals as movable at each bus. Further, the results obtained in each of the cases are compared with their feasible counterparts in order to establish a logical justification for the selection of algorithm as per the nature of the distribution network being catered to. The performance of the algorithm is evaluated by considering the following figures of merits like line loss, individual bus loading, branch current, neutral current, bus voltage and average unbalance index (AUI) $\left(\frac{\left|(S_a - S_b)\right| + \left|(S_b - S_c)\right| + \left|(S_c - S_a)\right|}{3}\right)$. The IEEE 13-bus test system is considered for the six cases mentioned above and backward-forward sweep load flow method is employed for computing the line loss, branch current, neutral current and bus voltage. Further, the feasibility of the developed algorithm is verified considering the IEEE 123-bus test feeder and a typical practical LV distribution feeder. Besides, the selection of the most favourable phase arrangement resulting in reduced interruptions as a result of time varying load is presented.

4.1 ALGORITHM 1: PHASE BALANCING OF SINGLE-PHASE CSMs AT EACH BUS

The line losses before and after balancing are 622.0379 kW and 584.7717 kW respectively resulting in a loss reduction of 5.99%. The feeder load profile and their AUI are listed in Table 4.1, and it can be inferred that there is an increase in its value from 175.725 to 203.149 reflecting that system is partially balanced. This is due to the non-consideration of three-phase CSMs despite their presence at various buses during balancing of the single-phase CSMs. The case mentioned above emerges when the feeder consists of single-phase CSMs alone, enhancing the suitability of the suggested algorithm.

Table 4. 1 Load profile and AUI for phase balancing of single-phase CSMs at each bus

	P_a (kW)	**P_b (kW)**	**P_c (kW)**	**Q_a (kVAR)**	**Q_b (kVAR)**	**Q_c (kVAR)**	**AUI**
Before balancing	1175	1039	1252	616	665	821	175.7255
After balancing	1088.796	1066.149	1311.054	612.2948	655.6363	834.0689	203.1496

From Fig. 4.1 it is observed that as a result of phase balancing there is a significant improvement in the various figures of merits considered. In particular, the following observations are highlighted to support the process of successful phase balancing.

At bus 9: It is evident that some of the single-phase CSMs of phase A are moved to phase B. As a result, an curtailment in unbalance is achieved as shown in Fig. 4.1(a) with reduction of phase A current and increase of phase B current at branch 8 (refer Fig 4.1 (b)), thereby reducing its neutral current (refer Fig. 4.1 (c)). An expected inverse behaviour of the voltage at bus 9 in contrast to the branch current is noticed in Fig 4.1(d).

At bus 8: It is observed that some of the single-phase CSMs of phase C is moved to phase A and B. It results in increased branch current in phase A and B and reduced branch current in phase C. The behavioural action of bus 8 is similar to bus 9.

At bus 6 and 5: It is observed that the single-phase CSMs of phase B is distributed among phase B and C. It results in increased branch current in phase C and reduced branch current in phase B. The behavioural action is similar to bus 9.

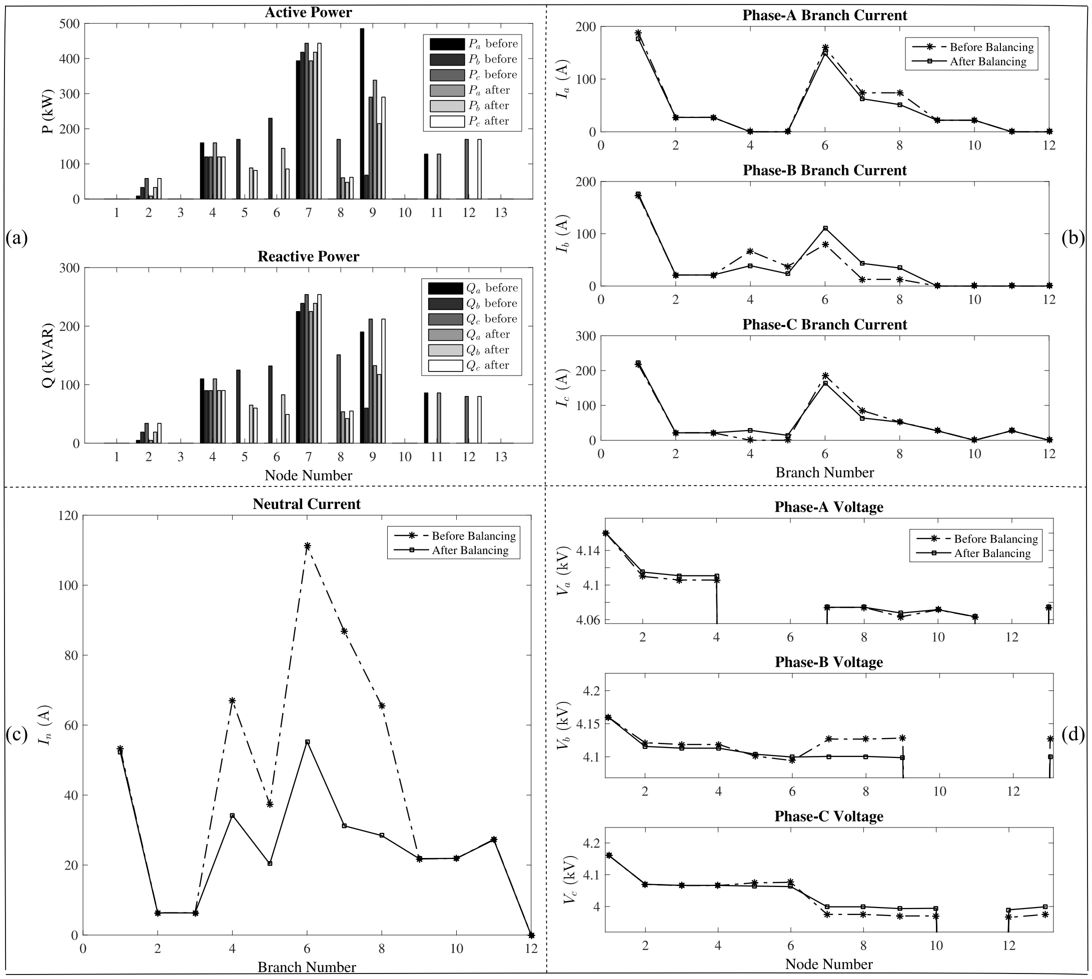


Figure 4. 1 Results for phase balancing of single-phase CSMs before and after balancing: (a) load profile (b) branch current (c) neutral current (d) node voltage.

4.2 ALGORITHM 2: PHASE BALANCING OF THREE-PHASE AND SINGLE-PHASE CSMs AT EACH BUS

The line losses before and after balancing are 622.0379 kW and 582.3019 kW respectively resulting in a loss reduction of 6.38%. The feeder load profiles and their AUI are listed in Table 4.2, and it can be inferred that there is an increase in its value from 175.725 to 251.64 reflecting that system is partially balanced. Here at a given bus, the three-phase CSMs and single-phase CSMs are balanced independently; however, the cumulative effect remains unbalanced as they are catered one at a time. This particular case emerges when the feeder consists of either single-phase CSMs or three-phase CSMs only at the bus, enhancing the suitability of the suggested algorithm.

Table 4. 2 Load profile and AUI for phase balancing of three-phase and single-phase CSMs at each bus

	P_a (kW)	**P_b (kW)**	**P_c (kW)**	**Q_a (kVAR)**	**Q_b (kVAR)**	**Q_c (kVAR)**	**AUI**
Before balancing	1175	1039	1252	616	665	821	175.7255
After balancing	972.3564	1197.74	1295.904	596.127	715.2983	790.5746	251.6476

From Fig. 4.2 it is observed that as a result of phase balancing there is a significant improvement in the various figures of merits considered. In particular, the following observations are highlighted to support the process of successful phase balancing.

At bus 9: It is evident that some of the single-phase CSMs of phase A are moved to phase B while leaving the three-phase CSMs balanced and vice versa. As a result, a curtailment in unbalance is achieved as shown in Fig. 4.2(a) with reduction of phase A current and increase of phase B current at branch 8 is observed in Fig 4.2 (b) thereby reducing its neutral current (Fig. 4.2 (c)). An expected inverse behaviour of the voltage at bus 9 in contrast to the branch current is noticed in Fig 4.2(d).

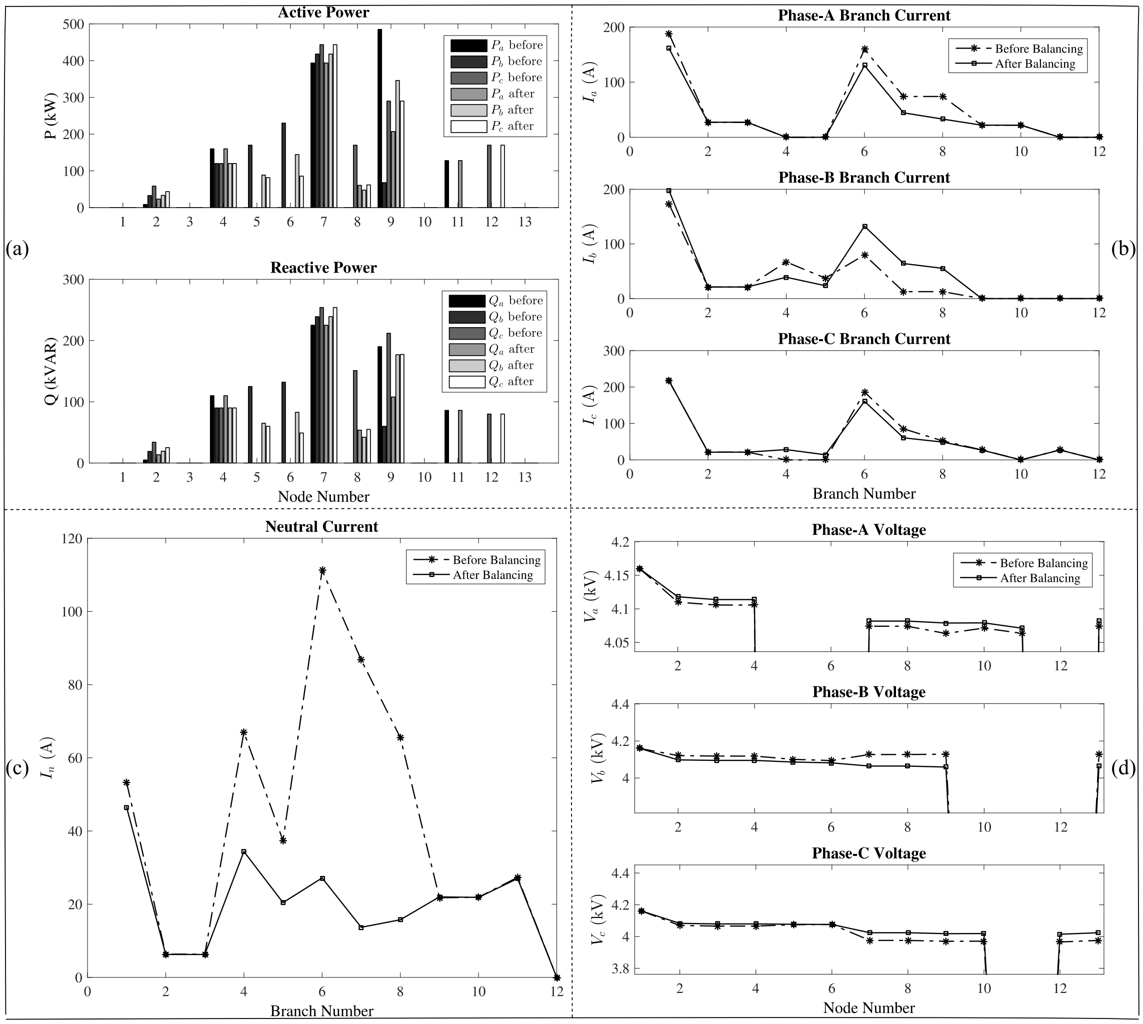


Figure 4. 2 Results for phase balancing of three-phase and single-phase CSMs before and after balancing: (a) load profile (b) branch current (c) neutral current (d) node voltage.

At bus 8: It is observed that some of the single-phase CSMs of phase C is moved to phase A and B. It results in increased branch current in phase A and B and reduced branch current in phase C. The behavioural action of bus 8 is similar to bus 9.

At bus 6 and 5: It is observed that the single-phase CSMs of phase B are distributed among phase B and C. It results in increased branch current in phase C and reduced branch current in phase B. The behavioural action is similar to bus 9.

Following the application of developed algorithms 1 and 2, a comparative evaluation is performed here to explicitly highlight the pros and cons of the said algorithms. By comparing the reduction in loss achieved as tabulated in Table 4.3, algorithm 2 further reduces the loss by 0.39%.

Table 4. 3 Comparison of loss incurred in algorithm 1 and algorithm 2

	Loss (kW)	**% Loss reduced**
Before Balancing	622.0379	-
Algorithm 1	584.7717	5.99%
Algorithm 2	582.3019	6.38%

From Fig. 4.3 it is worth mentioning that

I. There is an improvement in load profile at bus 9.
II. In branches 2, 5, 6, 7 and 8 the phase A current is reduced whereas phase B current is increased.
III. There is a reduction in neutral current in branches 2, 5, 6, 7 and 8.

It is evident from the above observations that, considering the three-phase CSMs and single-phase CSMs individually results in a better phase balancing in comparison to that of considering single-phase CSMs solely. However, from Table 4.4, the AUI is increased by 48.498 with the application of algorithm 2. Thus, when the loss reduction is of highest priority, it is suggested to employ algorithm 2 whereas algorithm 1 is preferred for the case where AUI is given the most priority.

Table 4. 4 Comparison of load profile and AUI for algorithm 1 and algorithm 2

	P_a (kW)	P_b (kW)	P_c (kW)	Q_a (kVAR)	Q_b (kVAR)	Q_c (kVAR)	AUI
Algorithm 1	1088.796	1066.149	1311.054	612.2948	655.6363	834.0689	203.1496
Algorithm 2	972.3564	1197.74	1295.904	596.127	715.2983	790.5746	251.6476

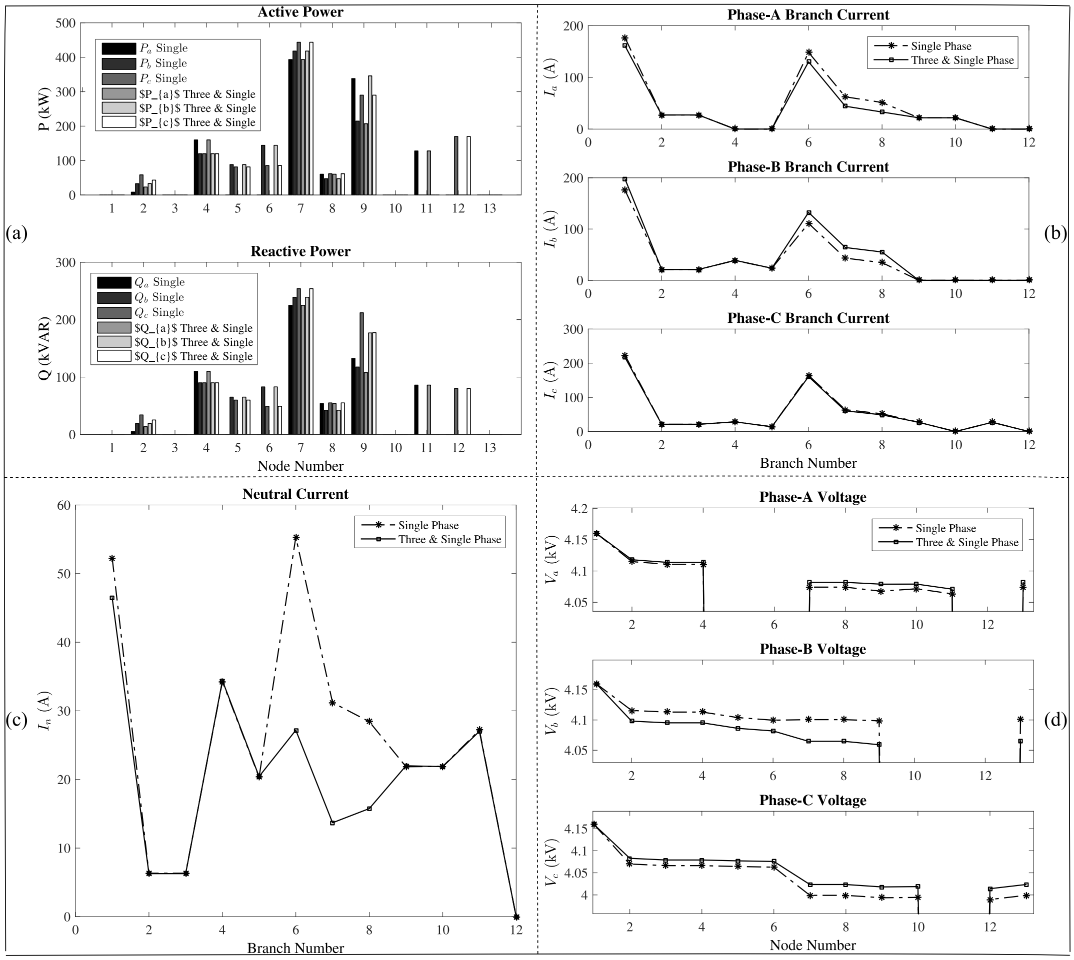


Figure 4. 3 Comparative results of algorithm 1 and 2: (a) load profile (b) branch current (c) neutral current (d) node voltage.

4.3 ALGORITHM 3: PHASE BALANCING OF THREE-PHASE AND SINGLE-PHASE CSMs AT EACH BUS, CONSIDERING THREE-PHASE CSMs AS LUMPED LOAD WHILE BALANCING SINGLE-PHASE CSMs

The motivation behind the development of this algorithm is to achieve a complete balancing of the bus, since algorithm 2 fails in achieving an overall adequate bus balancing. In this algorithm, referred to as algorithm 3, firstly the three-phase CSMs are balanced. Secondly the balancing of single-phase CSMs is carried out while considering the formerly balanced three-phase CSMs as lumped and immovable loads. With the application of algorithm 3, the line losses before and after balancing are 622.0379 kW and 580.9061 kW respectively with a loss reduction of 6.61%.

The feeder load profiles and their AUI are listed in Table 4.5, and it can be inferred that there is an increase in its value from 175.725 to 179.8123 reflecting that partial balance in the system is still prevailing. This fact is attributed to the non-uniform nature of the actual feeder (i.e., due to the presence of two-phase and single-phase feeder laterals).

Table 4. 5 Load profile and AUI for phase balancing of three-phase and single-phase CSMs by considering three-phase load as lumped while balancing single-phase CSMs at each bus

	P_a (kW)	P_b (kW)	P_c (kW)	Q_a (kVAR)	Q_b (kVAR)	Q_c (kVAR)	AUI
Before balancing	1175	1039	1252	616	665	821	175.7255
After balancing	1072.855	1097.24	1295.904	638.1464	673.279	790.5746	179.8123

From Fig. 4.4 it is observed that as a result of phase balancing there is a significant improvement in the various figures of merits. In specific, load at all buses are completely balanced as depicted in Fig. 4.4 (a). Thus, the developed algorithm can lead to an overall adequate balancing for system consisting of feeders with uniform structure.

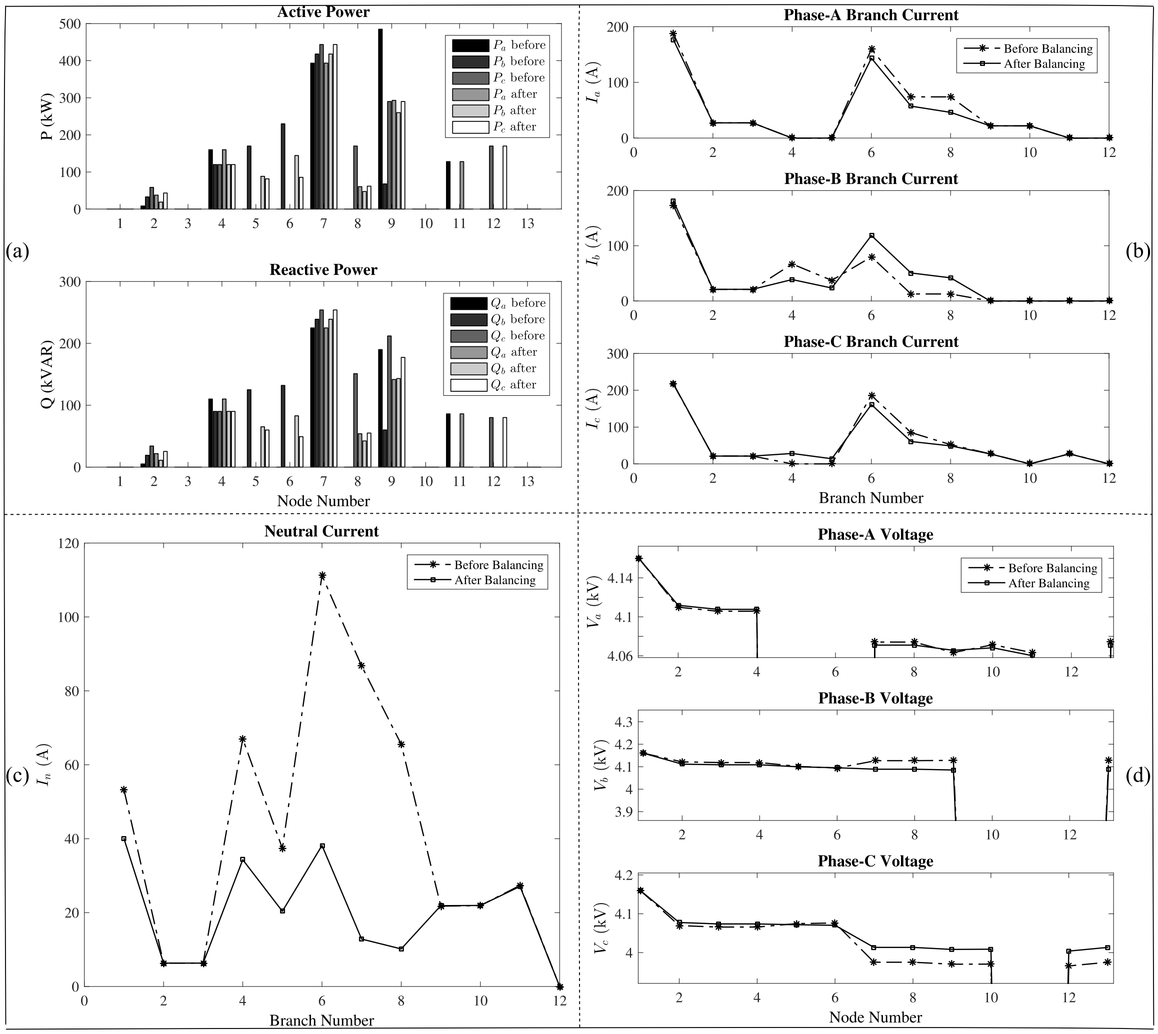


Figure 4. 4 Results for phase balancing of three-phase and single-phase CSMs by considering three-phase CSMs as lumped load while balancing single-phase CSMs before and after: (a) load profile (b) branch current (c) neutral current (d) node voltage.

Following the application of developed algorithms 2 and 3, a comparative evaluation is performed to highlight the pros and cons of the said algorithms. By comparing the reduction in loss achieved as tabulated in Table 4.6, algorithm 3 further reduces the loss by 0.23%.It is evident from the Fig. 4.5, algorithm 3 results in a better phase balancing in comparison to the algorithm 2. Thus, from the Table 4.7, the AUI is found to be decreased by 71.8347 with the application of algorithm 3. Therefore, it is suggested to employ algorithm 3 over the algorithm 2.

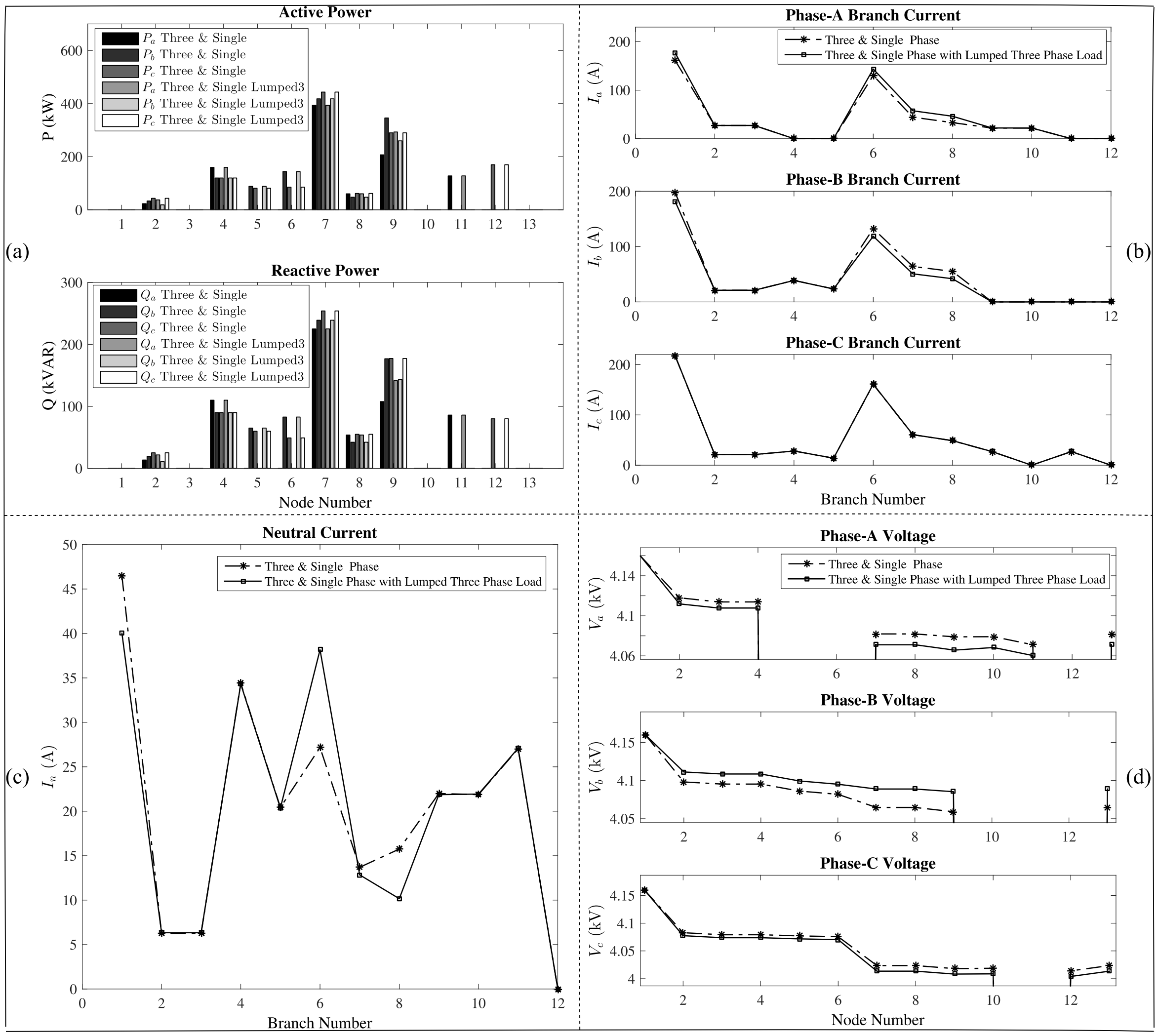


Figure 4. 5 Comparative results of algorithm 2 and 3: (a) load profile (b) branch current (c) neutral current (d) node voltage.

Table 4. 6 Comparison of loss incurred in algorithm 2 and algorithm 3

	Loss (kW)	**% Loss reduced**
Before Balancing	622.0379	-
Algorithm 2	582.3019	6.38
Algorithm 3	580.9061	6.61

Table 4. 7 Comparison of load profile and AUI for algorithm 2 and algorithm 3

	P_a (kW)	**P_b (kW)**	**P_c (kW)**	**Q_a (kVAR)**	**Q_b (kVAR)**	**Q_c (kVAR)**	**AUI**
Algorithm 2	972.3564	1197.74	1295.904	596.127	715.2983	790.5746	251.6476
Algorithm 3	1072.855	1097.24	1295.904	638.1464	673.279	790.5746	179.8123

4.4 ALGORITHM 4: PHASE BALANCING OF SINGLE-PHASE CSMs WITH BACKWARD SWEEP TECHNIQUE

In order to account for the non-uniformity in the feeder structure and thereby to attain maximum possible balancing, a backward sweep technique is used in conjunction with the previously developed algorithms. Thus, this combination results in the balance of network with respect to any arbitrary bus swept from the forward end. This particular advantage is emanated since the load on the rephased buses are considered as lumped/immovable load while balancing the preceding bus unlike algorithm 1 and 3. Wherein, only the load at the point of bus being balanced is considered while the rest of the loads balanced previously are disregarded.

The line losses before and after balancing are 622.0379 kW and 578.9564 kW respectively with a loss reduction of 6.92% with the application of algorithm 4. The feeder load profiles and their AUI are listed in Table 4.8, and it can be inferred that there is a decrease in its value from 175.725 to 167.7598 reflecting that the system has achieved an enhanced balance and is also evident from the plots in Fig. 4.6.

Table 4. 8 Load profile and AUI for phase balancing of single-phase CSMs using backward sweep technique

	P_a (kW)	**P_b (kW)**	**P_c (kW)**	**Q_a (kVAR)**	**Q_b (kVAR)**	**Q_c (kVAR)**	**AUI**
Before balancing	1175	1039	1252	616	665	821	175.7255
After balancing	1053.466	1221.835	1190.7	580.9129	789.3963	731.6908	167.7598

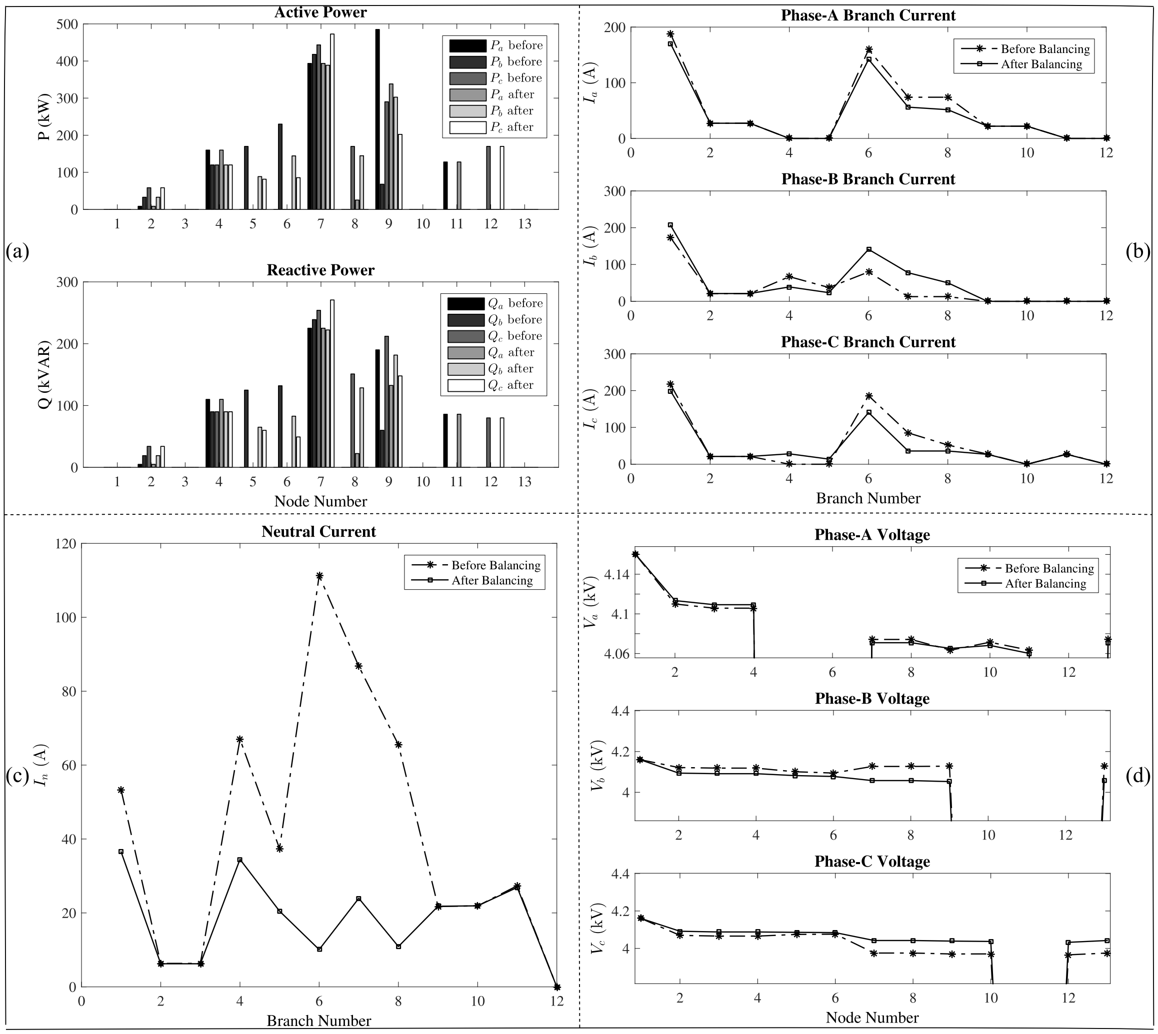


Figure 4. 6 Results for phase balancing of single-phase CSMs using backward sweep technique before and after balancing: (a) load profile (b) branch current (c) neutral current (d) node voltage.

Following the application of developed algorithms 1 and 4, a comparative evaluation is performed in order to explicitly highlight the pros and cons of the said algorithms. By comparing the reduction in loss achieved as tabulated in Table 4.9, algorithm 4 is found to further reduce the loss by 0.93%.

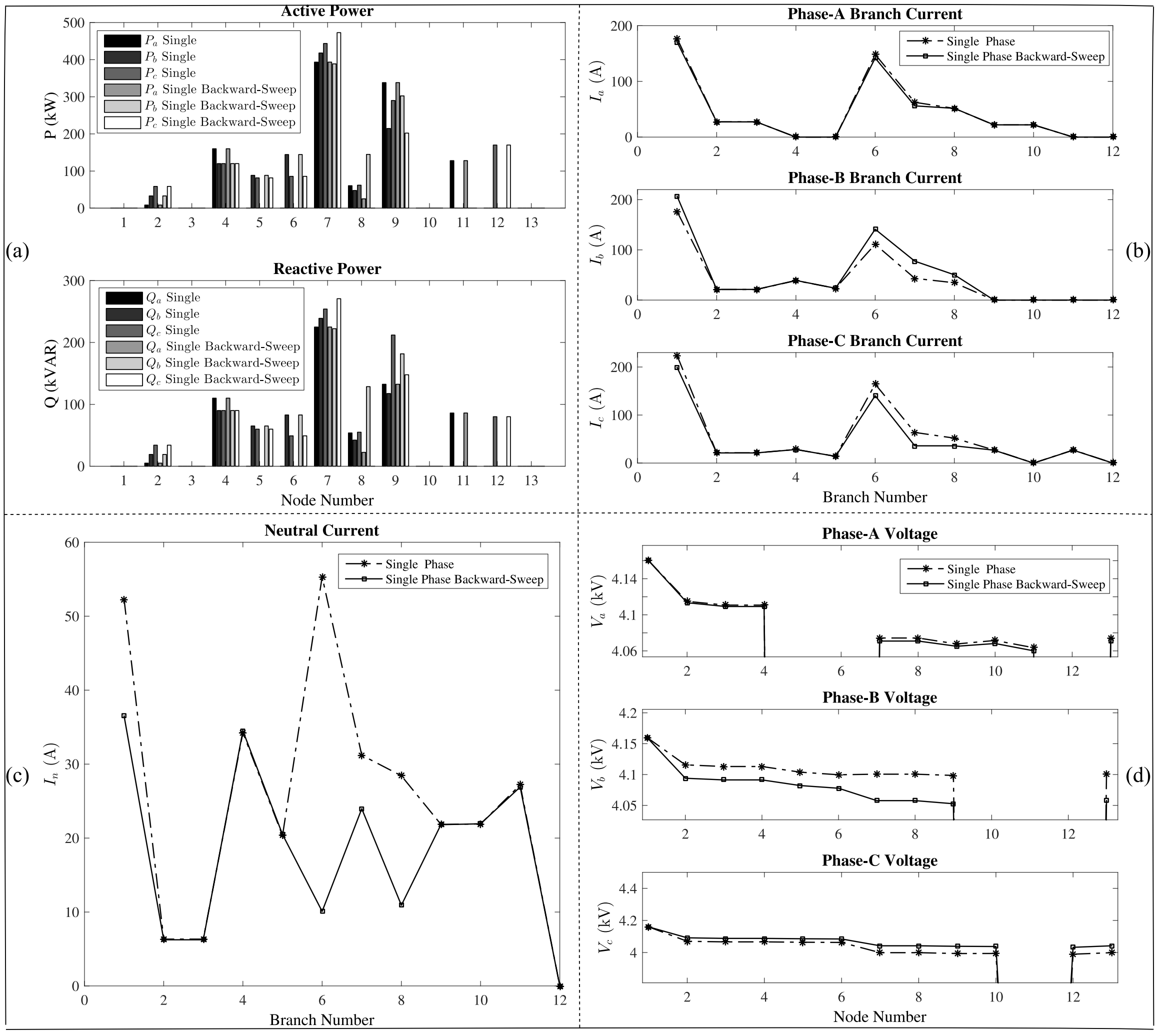


Figure 4. 7 Comparative results of algorithm 1 and 4: (a) load profile (b) branch current (c) neutral current (d) node voltage.

It is evident from the Fig. 4.7, the algorithm 4 outperforms the algorithm 1. Further, from the Table 4.10, the AUI is found to be decreased by 35.3898 with the application of algorithm 4. Therefore, it is suggested to employ algorithm 4 over the algorithm 1 in the case of non-uniform structured feeders with only single-phase CSMs.

Table 4. 9 Comparison of loss incurred in algorithm 1 and algorithm 4

	Loss (kW)	**% Loss reduced**
Before Balancing	622.0379	-
Algorithm 1	584.7717	5.99
Algorithm 4	578.9564	6.92

Table 4. 10 Comparison of load profile and AUI for algorithm 1 and algorithm 4

	P_a (kW)	**P_b (kW)**	**P_c (kW)**	**Q_a (kVAR)**	**Q_b (kVAR)**	**Q_c (kVAR)**	**AUI**
Algorithm 1	1088.796	1066.149	1311.054	612.2948	655.6363	834.0689	203.1496
Algorithm 4	1053.466	1221.835	1190.7	580.9129	789.3963	731.6908	167.7598

4.5 ALGORITHM 5: PHASE BALANCING OF THREE-PHASE AND SINGLE-PHASE CSMs WITH BACKWARD SWEEP

In contrary to algorithm 4, the presence of the three-phase CSMs is valued while balancing, and are considered as movable. The additional unbalance left out after balancing three-phase CSMs is corrected by adding/removing the single-phase CSMs appropriately. The notable benefit of this algorithm is that in addition to the individual bus, total network balancing is also achieved implicitly.

The line losses before and after balancing are 622.0379 kW and 581.1808 kW respectively with a loss reduction of 6.56% with the application of algorithm 5. The feeder load profiles and their AUI are listed in Table 4.11, and it can be inferred that there is a decrease of 45.99, implying that the system is well balanced and the same is also apparent from the plots in Fig. 4.8.

Table 4. 11 Load profile and AUI for phase balancing of three-phase and single-phase CSMs using backward sweep technique

	P_a (kW)	**P_b (kW)**	**P_c (kW)**	**Q_a (kVAR)**	**Q_b (kVAR)**	**Q_c (kVAR)**	**AUI**
Before balancing	1175	1039	1252	616	665	821	175.7255
After balancing	1058.926	1214.535	1192.539	626.1619	744.9563	730.8817	129.7307

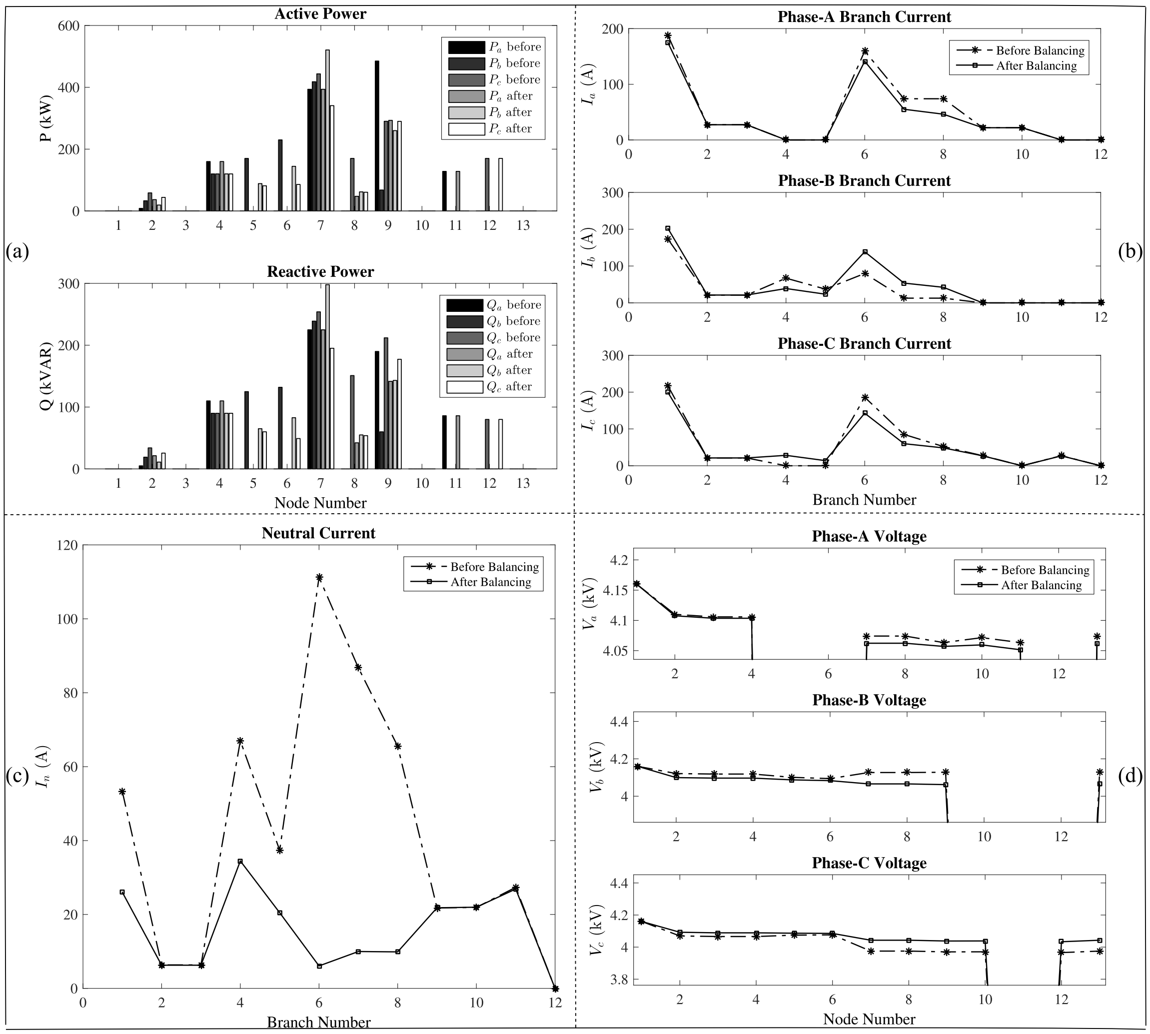


Figure 4. 8 Results for phase balancing of three-phase and single-phase CSMs using backward sweep technique before and after balancing: (a) load profile (b) branch current (c) neutral current (d) node voltage.

Following the application of developed algorithms 4 and 5, a comparative evaluation is performed here to explicitly highlight the pros and cons of the said algorithms. By comparing the reduction in loss achieved as tabulated in Table 4.12, algorithm 5 increases the loss by 0.36%.

Table 4. 12 Comparison of loss incurred in algorithm 4 and algorithm 5

	Loss (kW)	**% Loss reduced**
Before Balancing	622.0379	-
Algorithm 4	578.9564	6.92
Algorithm 5	581.1808	6.56

Further from the Fig. 4.9 it is worth mentioning that

I. There is an improvement in load profile at bus 9.
II. In branches 7, 8 and 9 the phase B current is reduced whereas phase C current is increased.
III. There is a reduction in neutral current in branches 2, 6, 7, 8 and 9.

It is evident from the above observations that, algorithm 5 results in better phase balancing in comparison to algorithm 4. Further, from the Table 4.13, the AUI is found to be decreased by 38.0291 with the application of algorithm 5. Thus, when the loss reduction is prime necessary, it is suggested to employ algorithm 4 whereas algorithm 5 is preferred for the case where AUI is of highest priority for overall feeder balancing.

Table 4. 13 Comparison of load profile and AUI for algorithm 4 and algorithm 5

	P_a (kW)	**P_b (kW)**	**P_c (kW)**	**Q_a (kVAR)**	**Q_b (kVAR)**	**Q_c (kVAR)**	**AUI**
Algorithm 4	1053.466	1221.835	1190.7	580.9129	789.3963	731.6908	167.7598
Algorithm 5	1058.926	1214.535	1192.539	626.1619	744.9563	730.8817	129.7307

Further, a comparative evaluation is performed here to explicitly highlight the pros and cons of the algorithms 2 and 5. By comparing the reduction in loss achieved as tabulated in Table 4.14, algorithm 5 further reduces the loss by 0.18%.

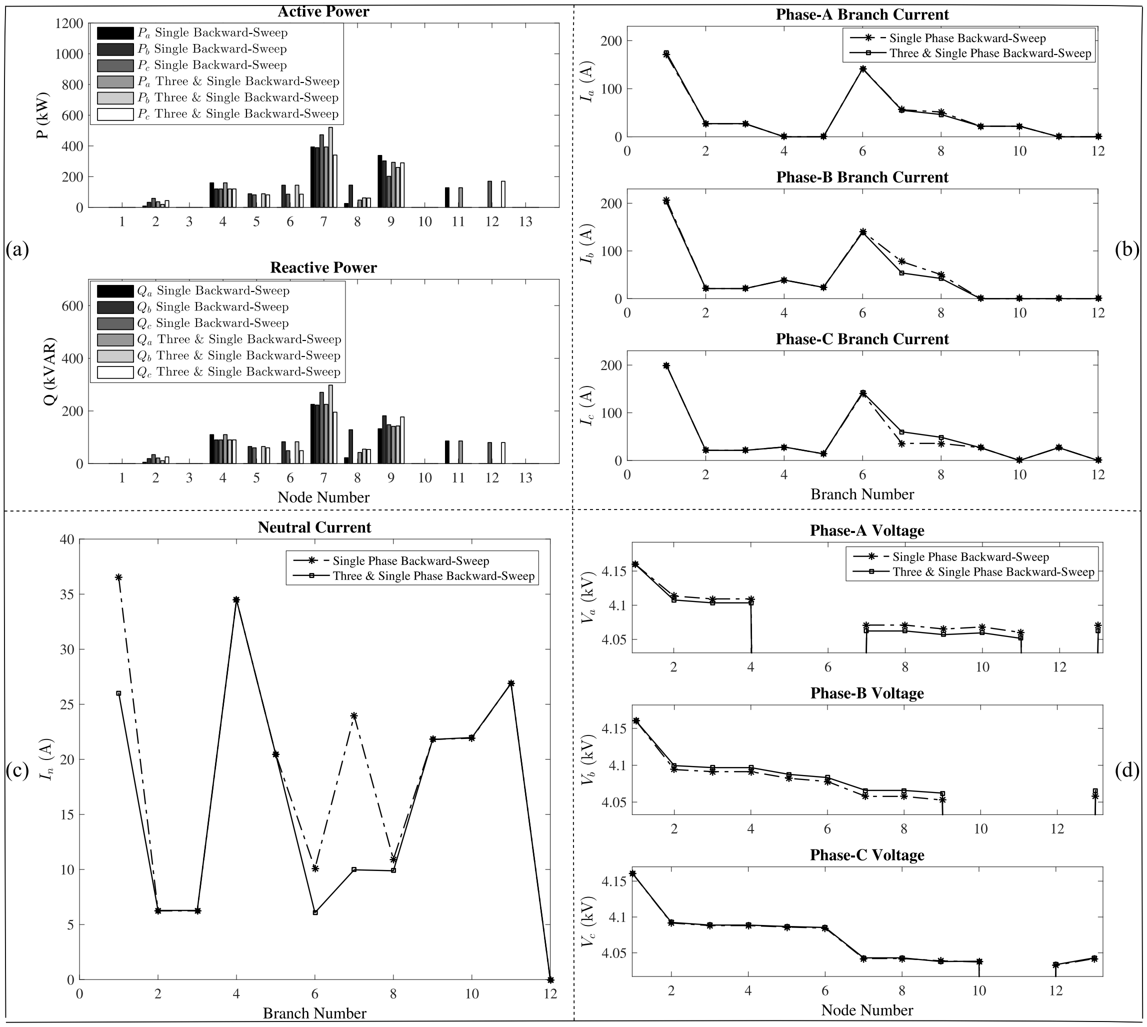


Figure 4. 9 Comparative results of algorithm 4 and 5: (a) load profile (b) branch current (c) neutral current (d) node voltage.

Table 4. 14 Comparison of loss incurred in algorithm 2 and algorithm 5

	Loss (kW)	**% Loss reduced**
Before Balancing	622.0379	-
Algorithm 2	582.3019	6.38
Algorithm 5	581.1808	6.56

It is evident from the Fig. 4.10, algorithm 5 results in a better overall feeder phase balancing in comparison to the algorithm 2. Further, from the Table 4.15, the AUI is found to be decreased by 121.9169 with the application of algorithm 5. Therefore, it is suggested to employ algorithm 5 over the algorithm 2 in the case of non-uniform structured feeders for overall feeder balancing.

Table 4. 15 Comparison of load profile and AUI for algorithm 2 and algorithm 5

	P_a (kW)	P_b (kW)	P_c (kW)	Q_a (kVAR)	Q_b (kVAR)	Q_c (kVAR)	AUI
Algorithm 2	972.3564	1197.74	1295.904	596.127	715.2983	790.5746	251.6476
Algorithm 3	1058.926	1214.535	1192.539	626.1619	744.9563	730.8817	129.7307

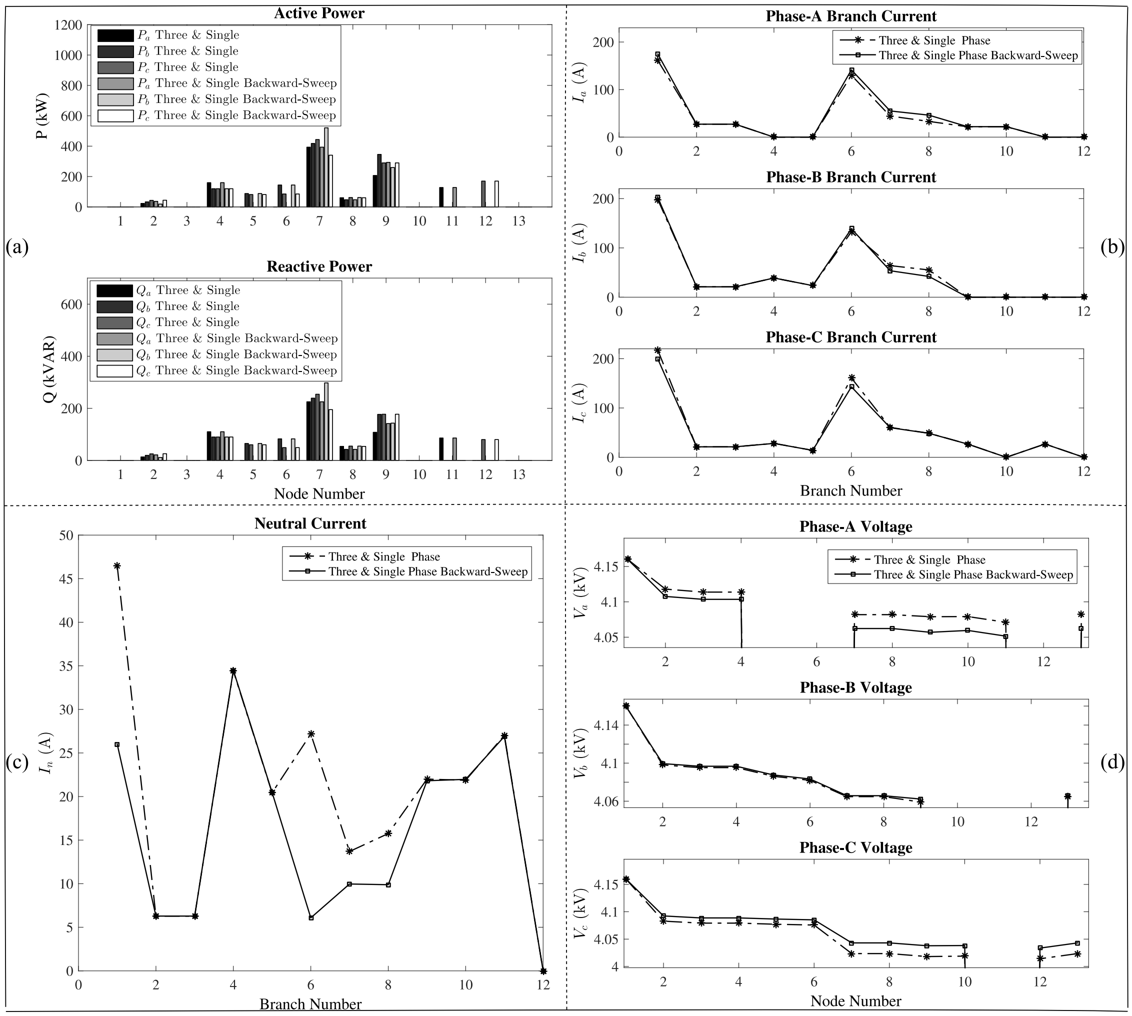


Figure 4. 10 Comparative results of algorithm 2 and 5: (a) load profile (b) branch current (c) neutral current (d) node voltage.

4.6 ALGORITHM 6: PHASE BALANCING OF THREE-PHASE AND SINGLE-PHASE CSMs WITH BACKWARD SWEEP BY CONSIDERING FEEDER LATERALS AS MOVABLE

Despite considering both three-phase and single-phase CSMs in the process of network balancing, a significant reduction in AUI and line loss collectively is unnoticeable after the application of algorithm 5. Further to enhance the balancing process, the feeder laterals are also considered as movable in addition to CSMs unlike algorithm 5 where feeder laterals were assumed immovable (wherein the motto was to achieve balancing only through CSM rephasings).

The line losses before and after balancing are 622.0379 kW and 564.723 kW respectively with a loss reduction of 9.21% following the application of algorithm 6. The feeder load profiles and their AUI are listed in Table 4.16, and it can be inferred that there is a decrease of 80.70 reflecting that system is well balanced. This particular algorithm is best suitable for the feeder with the presence of single-phase and two-phase feeder laterals (i.e., non-uniform feeder structure).

Table 4. 16 Load profile and AUI for phase balancing of three-phase and single-phase CSMs using backward sweep technique by considering feeder laterals as movable

	P_a (kW)	P_b (kW)	P_c (kW)	Q_a (kVAR)	Q_b (kVAR)	Q_c (kVAR)	AUI
Before balancing	1175	1039	1252	616	665	821	175.7255
After balancing	1228.461	1125.481	1112.058	754.8588	675.1717	671.9694	95.02359

Following the application of developed algorithms 5 and 6, a comparative evaluation is performed to explicitly highlight the pros and cons of the said algorithms. By comparing the reduction in loss achieved as tabulated in Table 4.17, algorithm 6 further reduces the loss by 2.65%.

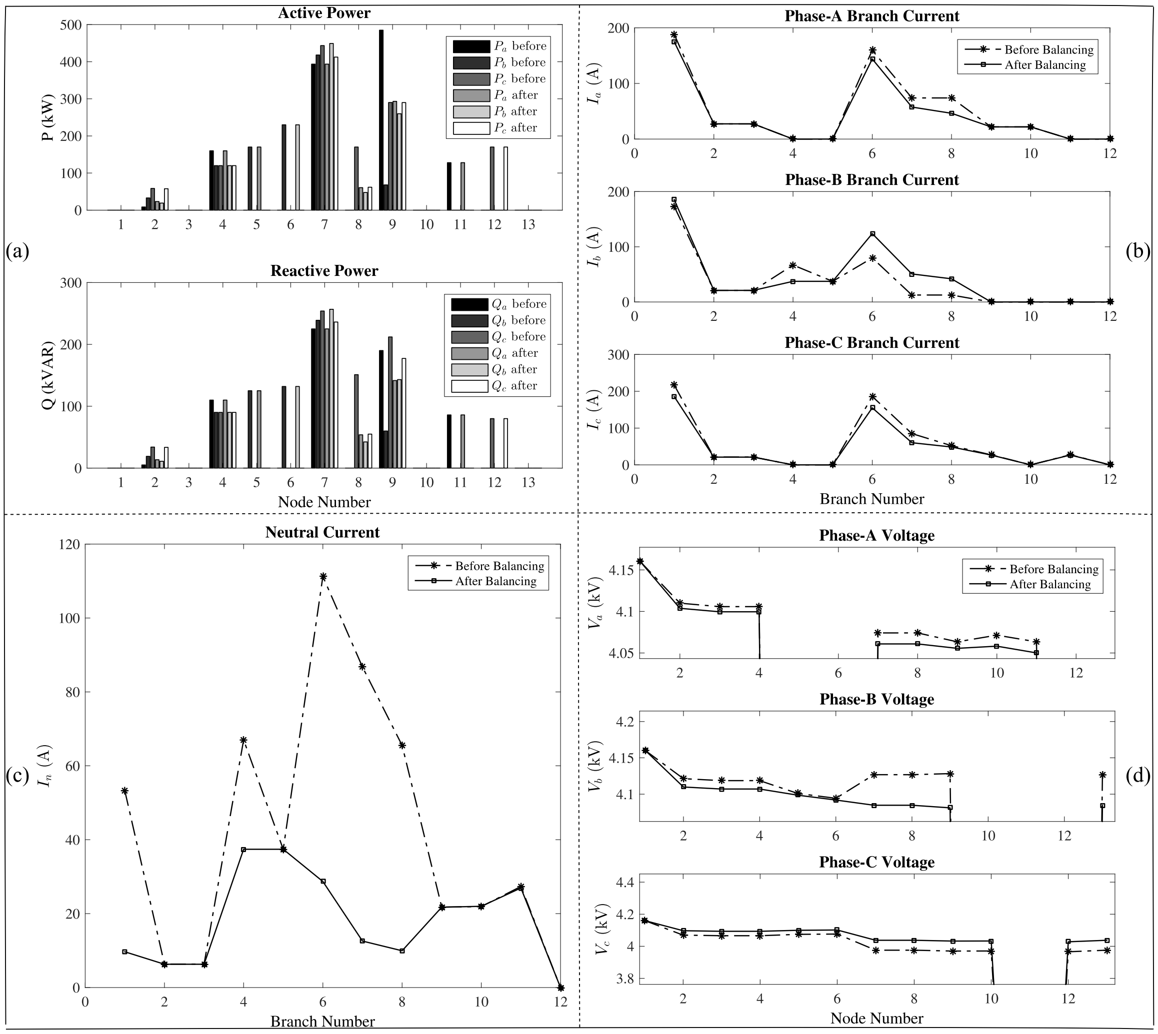


Figure 4. 11 Results for phase balancing of three-phase and single-phase CSMs using using backward sweep technique by considering feeder laterals as movable before and after balancing: (a) load profile (b) branch current (c) neutral current (d) node voltage.

Table 4. 17 Comparison of loss incurred in algorithm 5 and algorithm 6

	Loss (kW)	**% Loss reduced**
Before Balancing	622.0379	-
Algorithm 5	581.1808	6.56
Algorithm 6	564.723	9.21

It is evident from the Fig. 4.12, algorithm 6 results in a better phase balancing in comparison to the algorithm 5. Thus, from the Table 4.18, the AUI is found to be decreased by 34.707 with the application of algorithm 6. Therefore, it is suggested to employ algorithm 6 over the algorithm 5 in the case of non-uniform structured feeders to achieve the overall feeder balance.

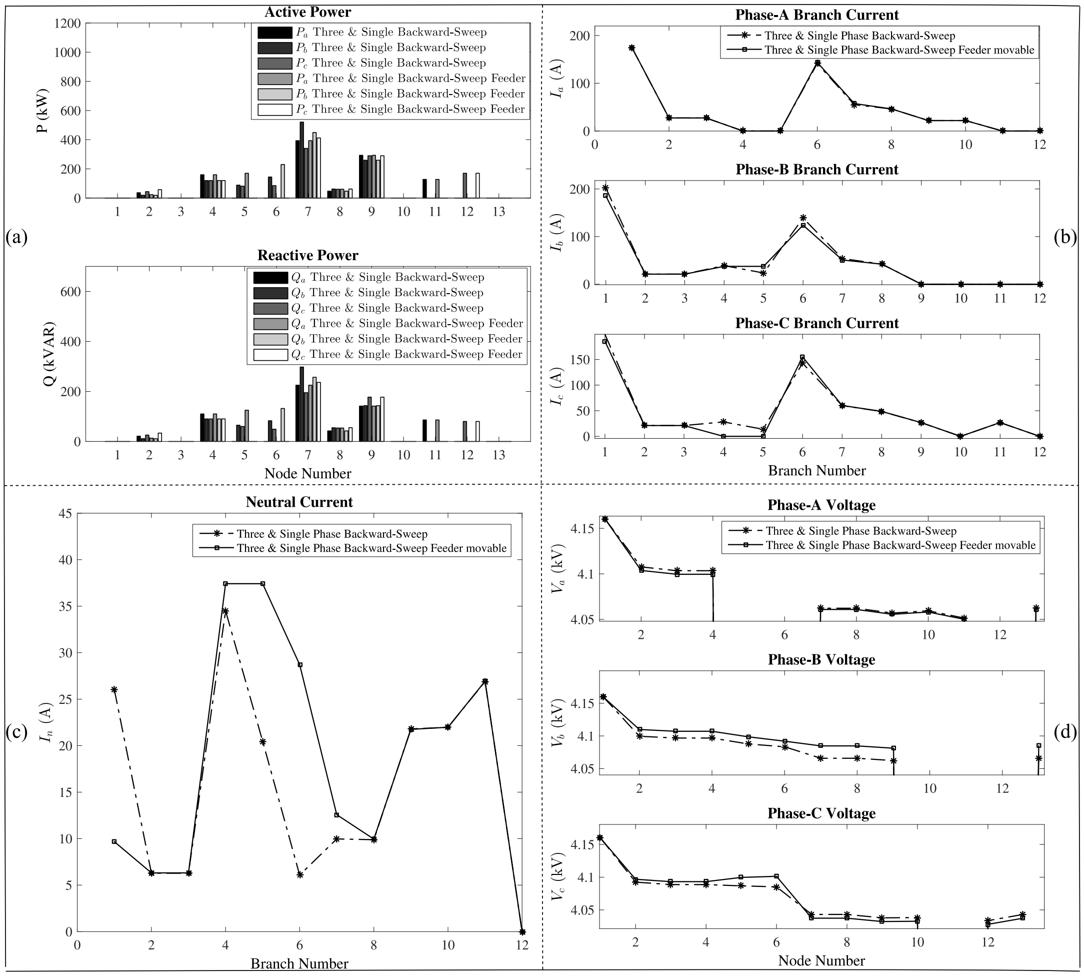


Figure 4. 12 Comparative results of algorithm 5 and 6: (a) load profile (b) branch current (c) neutral current (d) node voltage.

Table 4. 18 Comparison of load profile and AUI for algorithm 5 and algorithm 6

	P_a (kW)	P_b (kW)	P_c (kW)	Q_a (kVAR)	Q_b (kVAR)	Q_c (kVAR)	AUI
Algorithm 5	1058.926	1214.535	1192.539	626.1619	744.9563	730.8817	129.7307
Algorithm 6	1228.461	1125.481	1112.058	754.8588	675.1717	671.9694	95.02359

4.1COMPARISON OF PROPOSED PHASE BALANCING ALGORITHM WITH EXISTING TWO KINDS OF PHASE BALANCING ALGORITHMS CONSIDERING ONLY SINGLE-PHASE CSMs

To highlight the performance of the proposed algorithm, a comprehensive comparison with substation alone balancing (bus 1), and partial feeder balancing (at monitored buses) methods is carried out. Here algorithm 4 is chosen among six proposed algorithms, as it is the only suitable algorithm for single-phase CSMs alone. Since in the existing techniques, only single-phase CSMs are considered for balancing.

Table 4. 19 Comparison of load profile, AUI and %loss for different phase balancing methods

Balancing	P_a (kW)	P_b (kW)	P_c (kW)	Q_a (kVAR)	Q_b (kVAR)	Q_c (kVAR)	AUI	%loss
Before	1175	1039	1252	616	665	821	175.7255	-
At Bus 1	1200.517	1153.709	1111.774	630.8303	758.8998	712.2699	40.3765	3.25
At monitored buses	1175	1148.443	1142.557	616	762.2115	723.7885	34.45604	3.13
At each bus	1053.466	1221.835	1190.7	580.9129	789.3963	731.6908	167.7598	6.92

It can be observed from Table 4.19 that there is a significant loss reduction with the application of the algorithm 4. However, the methods discussed in literature concentrating on only selected candidate points (substation/ bus 1 is one among them) results in the least AUI, this does not imply that the balance of the entire feeder is achieved as shown in Fig. 4.13(a). This can be overcome by using the proposed algorithm. Further, it is evident from Fig. 4.13(b)-(d) with the application of algorithm 4; an overall significant improvement is witnessed.

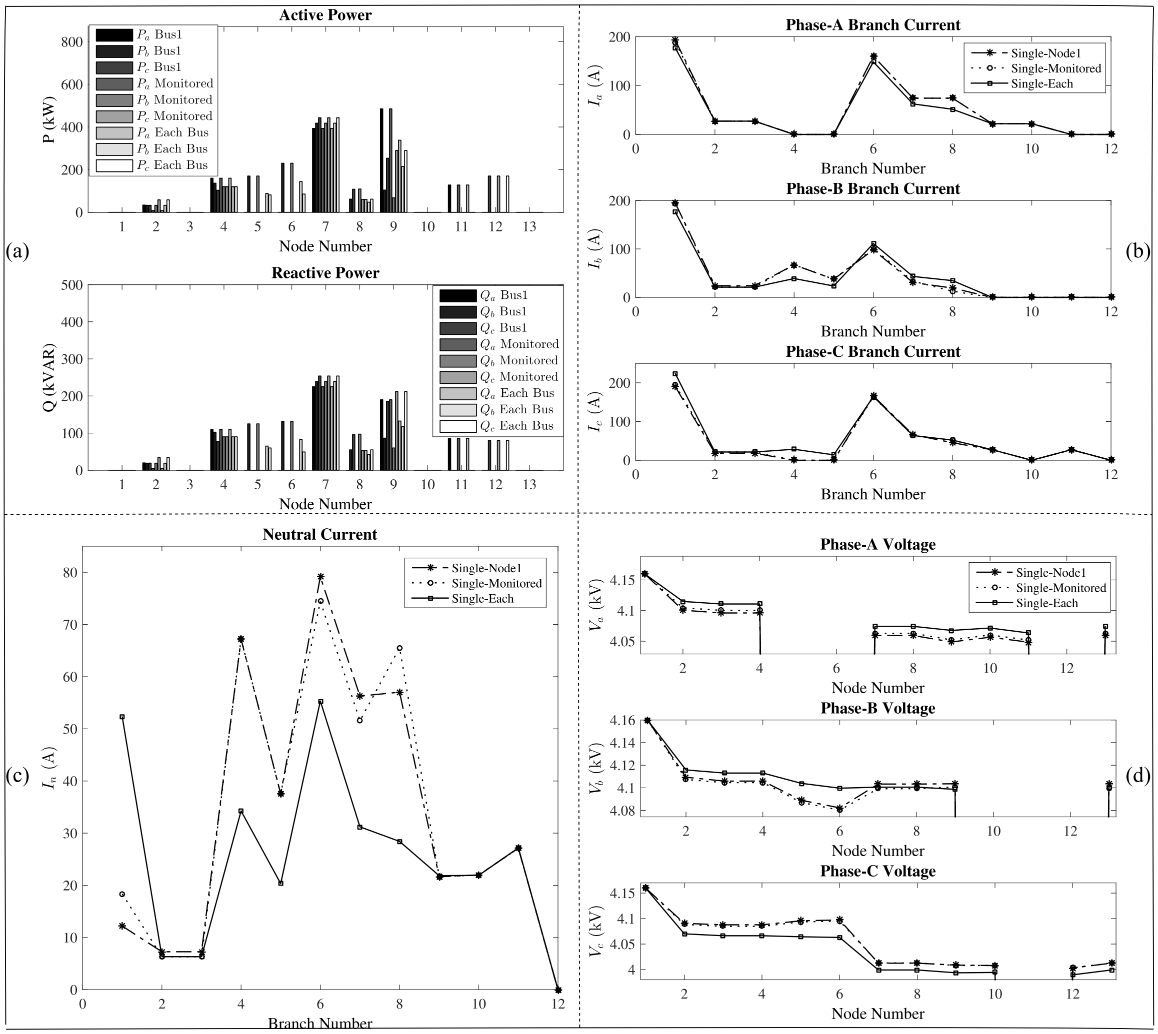


Figure 4. 13 Comparative results of proposed algorithm with 2 existing methods: (a) load profile (b) branch current (c) neutral current (d) node voltage.

4.2 APPLICATION TO IEEE 123-BUS TEST FEEDER

The IEEE 123-bus test feeder (refer Fig. 2.2) consists of more number of single-phase feeder laterals and also the number of buses having CSMs on three-phase feeder laterals are very few. For this case, algorithm 6 is more appropriate.

With the application of the algorithm, it is perceived that a reduction of 20.57% in line loss is achieved as listed in Table 4.20. It is also observed from the Table 4.21 that the AUI is reduced from 404.558 to 369.103. A much significant reduction in AUI is not witnessed since not all the buses are loaded. Fig. 4.14(a)-(c) shows the branch current, neutral current and node voltage profile respectively. From the figures, the reduced neutral currents and well distributed branch currents aiding the phase balancing at various branches confirms the appropriateness and correctness of the developed algorithm.

Table 4. 20 Line loss for phase balancing of IEEE 123-bus test feeder

Before Balancing Loss	10565.66 kW
After Balancing Loss	8391.864 kW
%Loss reduced	20.57%

Table 4. 21 Load profile and AUI for phase balancing of IEEE 123-bus test feeder

	P_a (kW)	**P_b (kW)**	**P_c (kW)**	**Q_a (kVAR)**	**Q_b (kVAR)**	**Q_c (kVAR)**	**AUI**
Before balancing	1420	915	1125	830	490	630	404.558
After balancing	1391.895	906.0162	1162.089	785.1317	519.5386	645.3297	369.1038

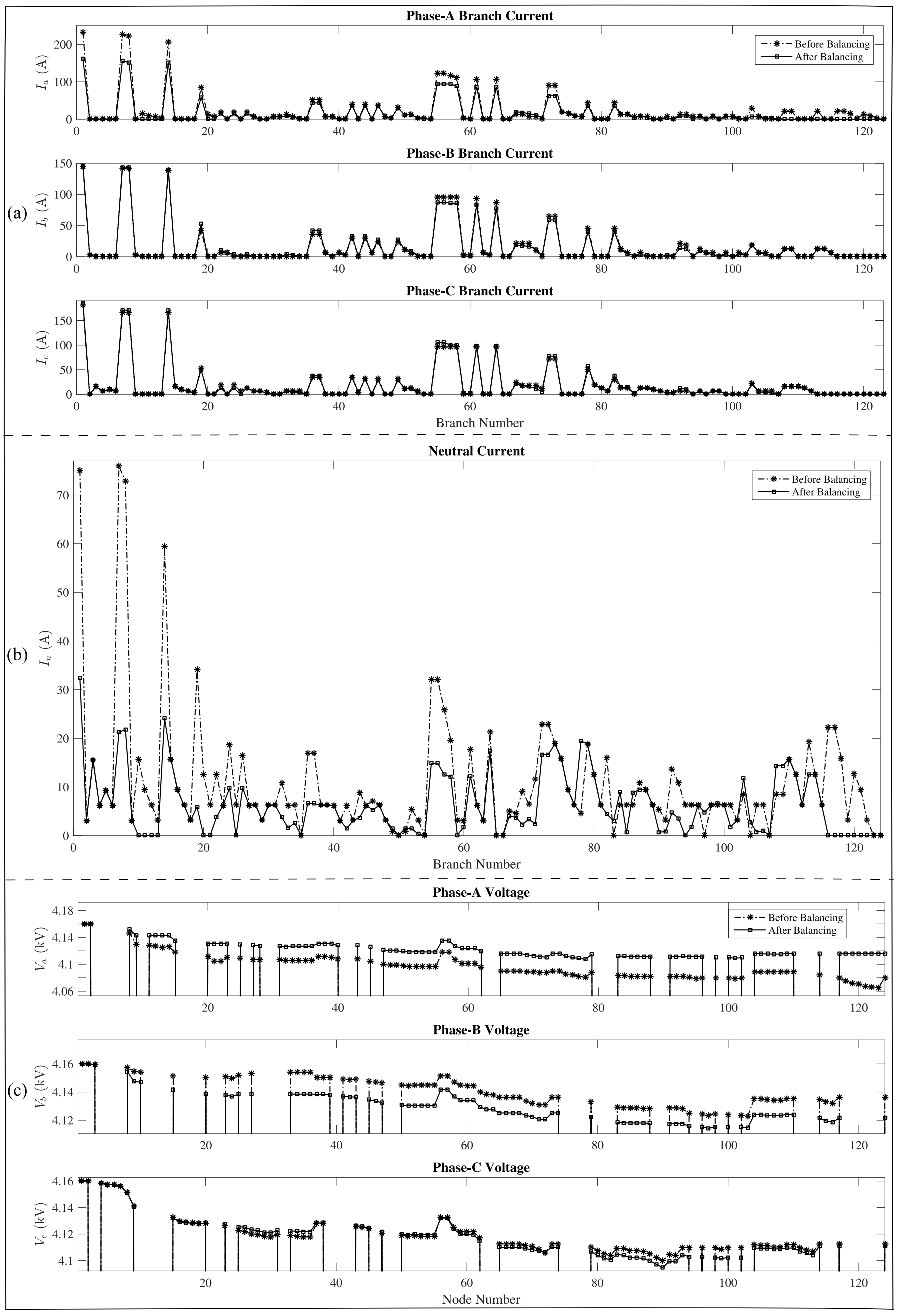


Figure 4. 14 Results for phase balancing of IEEE 123-bus test feeder before and after balancing: (a) branch current (b) neutral current (c) node voltage

4.3APPLICATION TO 16-BUS LV TYPICAL SYSTEM OF MYSURU

Further to validate the developed algorithm, a typical practical secondary distribution system is employed. A 16-bus LV feeder emanating from 100 kVA distribution transformer located at Mysuru is the test system considered. It houses adequate smart meters deployed as a part of the pilot project where from the corresponding CSMs data (9 PM on 19th Feb 2017) is obtained. Structurally it is a three-phase four wire system consisting of only single-phase CSMs. Among the algorithms developed, algorithm 1 is suitable for this particular case owing to the presence of only single-phase CSMs and uniformity in the feeder. It is also observed from the Table 4.22 that there is a significant reduction in AUI of 403.5 corroborating the effective phase balancing achieved. A noticeable line loss reduction of 51.823% from Table 4.23 exemplifies and thereby qualifies the proposed algorithm as a potential alternative candidate for the loss reduction in the secondary distribution system. All these merits of reduced neutral current at every branch, improved node voltage profile and a well-distributed branch currents are depicted in Fig. 4.15 (b)-(d).

Table 4. 22 Load profile and AUI for phase balancing of 16-bus LV typical system

	P_a (kW)	**P_b (kW)**	**P_c (kW)**	**Q_a (kVAR)**	**Q_b (kVAR)**	**Q_c (kVAR)**	**AUI**
Before balancing	251.0102	851.2807	423.3045	63.69602	206.3136	58.80073	411.3059
After balancing	507.4907	517.6268	500.4779	89.72637	99.29298	139.791	7.801654

Table 4. 23 Line loss for phase balancing of 16-bus LV typical system of Mysuru

Before balancing loss	290.921 kW
After balancing loss	140.189 kW
%Loss reduced	51.82%

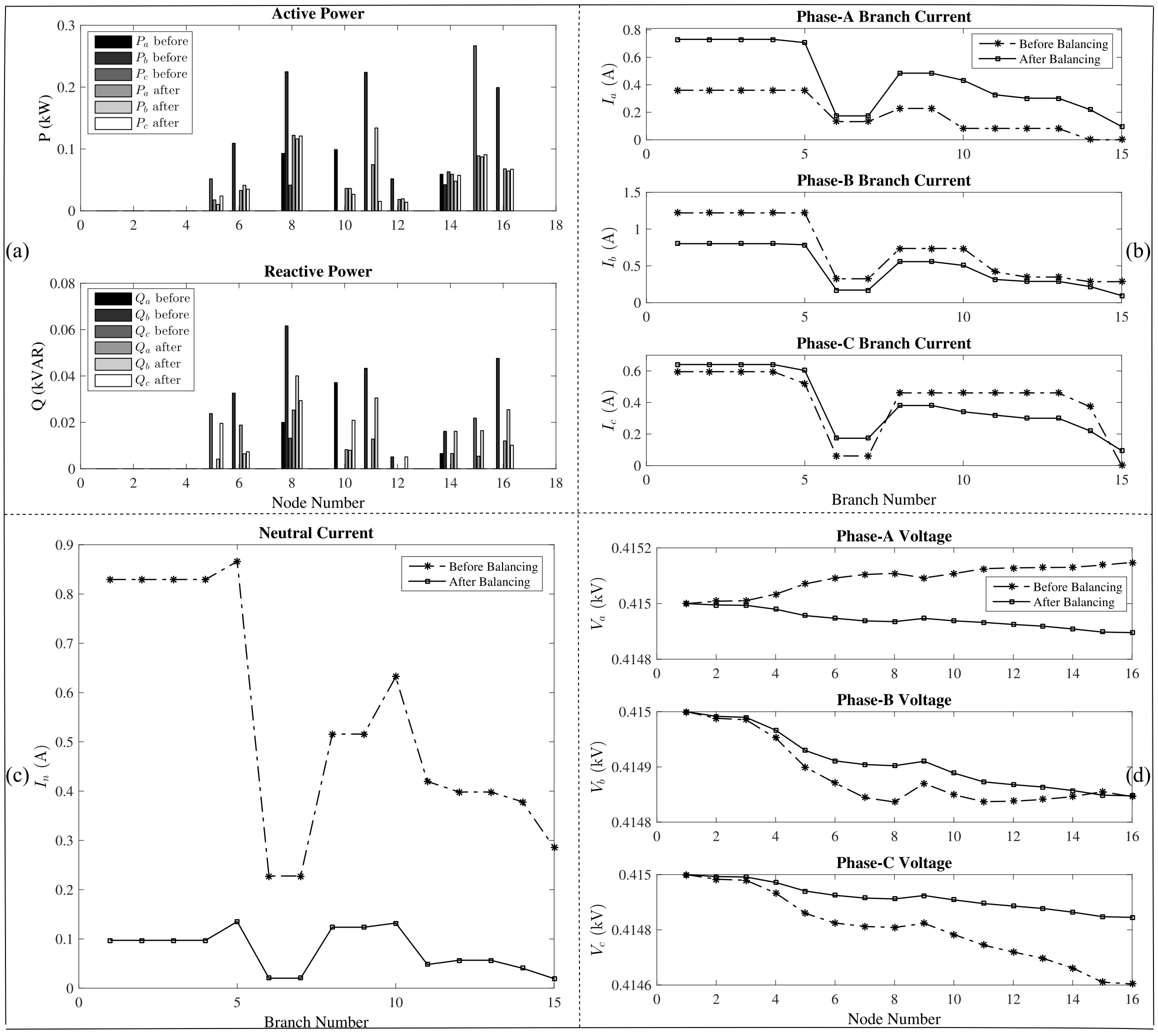


Figure 4. 15 Results for phase balancing of 16-bus LV typical system of Mysuru before and after balancing: (a) load profile (b) branch current (c) neutral current (d) node voltage

4.4 SELECTION OF MOST FAVOURABLE PHASE ARRANGEMENT of CSMs

To make the proposed algorithm devoid of many number of interruptions caused as a result of instantaneous phase balancing and to cope up with time varying nature of the load, an upgrade to the developed algorithms is proposed. This upgrade includes the selection of a particular phase arrangement of CSMs such that it results in minimum line loss over the stipulated chosen period. The rationale behind the selection of a particular phase arrangement is described vividly wherein the 24th Feb 2017 CSMs data corresponding to the typical practical system with a time interval of 1 hour. Following the method described in Sec 3.2, it is found from the Table 4.24 that the arrangement A11 leads to an overall minimum line loss (280.09 kW) over the day selected, in comparison to the other phase arrangements generated by algorithm 1. Even though the resulting line losses post application of arrangement A11 is higher than that of the line losses occurring from instantaneous phase balancing (244.94 kW), the number of rephasing required in the former case is only once while the latter need 24 times of rephasings. Carrying out a similar procedure over a considerable period (weekly, monthly, seasonal) empowers the system operator to maintain the distribution system remains less intact as a result of reduced number of rephasings, interruption and line losses. On the other hand, this necessitates the collection of individual CSM load profiles at regular intervals, which is possible only through the inclusion of smart meters with associated communication infrastructure into the conventional power distribution system thereby making it a smart power distribution system.

Table 4. 24 Loss corresponding to input and phase arrangement in kW

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20	A21	A22	A23	A24
Input1	8.21	9.33	9.21	8.69	9.19	8.37	8.69	9.11	8.91	8.81	8.80	8.82	8.78	12.90	8.97	10.35	10.87	14.17	9.23	9.60	8.71	8.57	8.27	8.50
Input2	11.42	8.82	13.07	12.26	11.97	10.27	12.43	11.61	11.58	11.17	11.56	11.81	11.18	14.96	12.00	11.75	9.24	14.47	10.22	12.58	10.71	10.91	11.30	10.91
Input3	9.02	8.83	7.50	8.45	7.97	8.14	9.33	8.24	9.89	9.03	8.49	8.22	8.42	12.86	8.75	8.67	8.85	12.30	8.71	8.96	8.46	9.06	7.52	8.62
Input4	7.84	8.00	7.69	6.68	7.97	7.83	8.15	7.82	7.58	7.59	7.35	8.59	7.60	10.74	7.81	8.59	8.57	9.01	8.75	7.60	7.54	7.66	7.91	7.59
Input5	7.53	7.11	7.44	6.81	6.08	6.86	7.02	7.49	6.85	7.00	7.35	7.08	6.79	9.17	7.65	7.23	8.17	7.47	6.76	6.47	7.32	7.04	6.65	6.88
Input6	7.39	7.96	7.56	7.04	7.08	6.82	7.53	6.94	7.58	7.28	7.80	7.52	7.15	10.14	8.14	8.50	7.26	8.29	7.28	8.26	7.30	7.58	6.87	7.41
Input7	6.82	8.26	7.14	7.17	6.65	6.81	6.39	7.04	6.49	6.50	6.78	7.54	6.84	9.03	9.46	9.06	8.49	8.12	7.78	6.90	6.78	6.84	6.77	7.40
Input8	6.68	7.32	6.66	6.77	6.24	6.59	6.76	6.26	6.24	6.37	6.83	6.30	6.17	8.92	8.29	7.80	6.85	8.50	6.58	7.38	6.45	6.62	6.29	6.20
Input9	7.78	8.34	7.67	7.66	7.68	7.69	7.99	7.36	6.39	7.40	7.07	7.80	8.03	11.13	10.07	8.36	7.79	9.10	8.75	7.21	7.21	7.69	7.16	7.44
Input10	7.25	6.88	7.77	8.67	7.58	7.81	8.76	6.98	7.15	6.47	6.90	8.94	7.74	9.89	7.14	7.53	7.83	11.34	7.90	6.70	7.02	6.86	7.11	7.29
Input11	8.72	10.19	7.61	8.21	8.00	7.79	7.87	7.98	8.30	8.19	6.74	7.92	8.79	10.67	7.63	7.65	8.71	8.96	8.47	7.35	6.94	8.39	7.00	8.46
Input12	11.66	9.98	11.10	10.31	9.84	11.35	12.19	9.46	9.33	9.34	8.77	8.66	13.64	15.78	9.58	13.87	9.85	10.77	11.76	11.91	11.34	10.77	11.16	11.71
Input13	10.46	13.30	11.94	11.47	12.07	10.71	11.57	12.14	9.74	10.86	10.05	15.61	9.03	13.35	11.20	13.29	14.37	10.64	12.88	10.22	11.84	10.78	10.67	11.52
Input14	15.57	13.41	14.66	15.45	14.06	13.46	14.14	14.99	11.46	11.97	12.95	16.05	17.12	12.79	11.65	13.87	12.19	11.73	11.87	15.50	14.34	11.32	14.18	14.12
Input15	15.84	17.58	15.77	20.58	18.67	17.19	15.41	15.61	13.33	13.76	15.30	23.97	18.47	21.34	12.89	19.60	13.18	16.76	17.25	17.56	16.76	15.64	17.77	15.98
Input16	12.47	14.29	12.10	13.49	11.02	13.59	13.25	11.72	10.61	10.79	12.34	10.34	15.88	17.37	11.56	8.65	12.11	10.65	13.80	9.81	10.59	13.61	12.29	12.79
Input17	27.20	23.11	27.63	25.10	23.53	24.23	29.08	26.10	25.30	31.05	23.81	26.15	26.42	36.59	29.27	40.37	23.11	26.10	34.78	28.46	23.72	25.79	24.68	27.86
Input18	23.93	35.97	37.13	34.23	32.69	33.93	28.58	32.06	33.64	32.22	24.98	29.76	28.38	37.41	25.89	29.46	31.53	21.53	37.73	27.65	29.01	32.13	23.51	31.79
Input19	19.30	14.31	15.37	18.26	16.54	20.20	18.82	16.68	15.46	17.23	18.12	20.16	22.93	22.70	19.97	17.03	16.07	15.89	13.04	20.31	18.62	15.69	18.81	14.83
Input20	10.69	12.41	11.39	13.19	11.21	11.51	12.03	12.40	11.45	14.68	16.22	11.14	12.00	12.89	12.31	12.51	14.53	12.00	21.86	9.94	14.22	15.70	10.82	10.08
Input21	16.32	17.03	18.40	15.65	15.54	18.00	19.58	16.75	16.58	15.02	15.65	26.25	19.90	21.45	16.58	21.29	17.55	17.32	18.63	17.35	13.40	22.79	21.10	14.46
Input22	12.25	15.10	12.12	17.78	12.77	16.12	12.95	16.10	11.70	16.30	15.54	12.73	14.99	18.69	12.66	22.37	24.01	11.52	19.78	13.52	17.36	11.50	11.78	18.45
Input23	16.88	18.73	14.70	17.71	15.12	16.02	22.38	17.60	18.62	13.53	12.24	14.49	24.32	16.75	13.32	12.66	15.67	17.17	17.35	12.21	12.48	14.42	15.18	13.62
Input24	13.44	8.32	8.92	8.39	8.26	9.27	8.29	8.63	8.66	8.49	8.46	9.16	8.98	10.06	10.24	10.42	9.26	10.67	12.16	9.37	9.50	8.56	8.10	8.85
	294.64	**304.57**	**300.55**	**310.03**	**287.74**	**300.56**	**309.19**	**297.07**	**282.84**	**291.06**	**280.09**	**315.00**	**319.54**	**377.57**	**293.03**	**330.87**	**306.08**	**304.48**	**333.31**	**292.81**	**287.61**	**295.95**	**282.90**	**292.76**

*Sum of diagonal elements is 244.34kW

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

Phase balancing is one of the preferred methods in secondary distribution energy management. The reported literature review reveals that efforts toward the improvement of phase balancing are less appreciable. This work presents the development of an algorithm for the whole feeder balancing comprising of three-phase CSMs, single-phase CSMs and movable feeder laterals.

A simple mathematical formulation-based algorithms (six in number) are developed for balancing (a) single-phase CSMs alone, (b) three-phase and single-phase CSMs, (c) three-phase and single-phase CSMs by considering three-phase load as lumped load while balancing single-phase CSMs, (d) single-phase CSMs alone using backward sweep technique, (e) three-phase and single-phase CSMs using backward sweep technique, (f) three-phase and single-phase CSMs using backward sweep technique by considering feeder laterals as movable at each bus respectively with an objective of line loss reduction, minimum number of phase moves, branch current and neutral current reduction and enhanced voltage profile. The performance of the developed algorithms is evaluated by considering the IEEE 13-bus and 123-bus bus test feeders systems and typical system data pertaining to 11 kV feeder at Mysuru, India.

Following the successful evaluation of algorithms for the above said cases it is worth mentioning that for IEEE 13-bus and 123-bus test feeders, algorithm 6 is more appropriate. Whereas, for the typical practical feeder system, algorithm 1 is best fitted and found to have a substantial line loss reduction of 51.82%.

Also, to contemplate the regular interruptions in power supply due to time varying load as a result of instantaneous phase balancing, a method for the selection of phase arrangement (resulting in minimum aggregate loss and a minimum number of phase moves) qualifying as a favourable phase sequence of CSMs is devised.

In a nutshell, the work presented in this thesis has addressed the unattended phase balancing methods by considering a holistic approach including all possible feeder and CSM nature, thereby improving the system performance. The work carried out also serves as a platform for balancing the system with a flexibility to operate in both uni-directional and bi-directional power flow in a smart grid environment. The developed algorithm is foreseen to be a feasible solution owing to the current deployment of smart meters for LV consumers.

Owing to the current integration of many renewable energy sources like roof-top photovoltaic, electric vehicle, biogas, etc., into the distribution utility, it is imperative to include their presence in phase balancing. One of the ways to achieve this is by considering such sources as the negative lumped load in the process of balancing the bus while keeping the remaining aspects intact, which is worth investigating. Also, an amalgamation of the developed algorithms with other factors that contribute to the unbalancing due to harmonics and low power factor is another aspects that demands further investigation.

APPENDIX I

IEEE 13-BUS TEST FEEDER

Before Balancing

Sl.No	Phase	Seq	P_a	P_b	P_c	Q_a	Q_b	Q_c	Bus
1	1	0	1.80	0.00	0.00	1.06	0.00	0.00	2
2	1	0	1.91	0.00	0.00	1.12	0.00	0.00	2
3	1	1	0.00	6.97	0.00	0.00	4.02	0.00	2
4	1	1	0.00	7.42	0.00	0.00	4.27	0.00	2
5	1	2	0.00	0.00	12.36	0.00	0.00	7.19	2
6	1	2	0.00	0.00	13.15	0.00	0.00	7.64	2
7	3	0	0.70	2.71	4.81	0.41	1.56	2.80	2
8	3	0	1.72	6.68	11.85	1.01	3.85	6.89	2
9	3	0	1.66	6.44	11.42	0.98	3.71	6.64	2
10	3	0	0.41	1.60	2.83	0.24	0.92	1.65	2
11	3	0	0.30	1.17	2.07	0.18	0.67	1.21	2
12	1	0	22.06	0.00	0.00	15.17	0.00	0.00	4
13	1	0	42.49	0.00	0.00	29.21	0.00	0.00	4
14	1	1	0.00	16.55	0.00	0.00	12.41	0.00	4
15	1	1	0.00	31.87	0.00	0.00	23.90	0.00	4
16	1	2	0.00	0.00	16.55	0.00	0.00	12.41	4
17	1	2	0.00	0.00	31.87	0.00	0.00	23.90	4
18	3	0	15.07	11.30	11.30	10.36	8.48	8.48	4
19	3	0	25.91	19.43	19.43	17.81	14.58	14.58	4
20	3	0	9.91	7.43	7.43	6.81	5.57	5.57	4
21	3	0	33.26	24.95	24.95	22.87	18.71	18.71	4
22	3	0	11.29	8.47	8.47	7.76	6.35	6.35	4
23	1	1	0.00	28.15	0.00	0.00	20.70	0.00	5
24	1	1	0.00	38.90	0.00	0.00	28.60	0.00	5
25	1	1	0.00	49.57	0.00	0.00	36.45	0.00	5
26	1	1	0.00	53.38	0.00	0.00	39.25	0.00	5
27	1	1	0.00	115.19	0.00	0.00	66.11	0.00	6
28	1	1	0.00	29.18	0.00	0.00	16.75	0.00	6
29	1	1	0.00	31.43	0.00	0.00	18.04	0.00	6

Sl.No	Phase	Seq	P_a	P_b	P_c	Q_a	Q_b	Q_c	Bus
30	1	1	0.00	54.21	0.00	0.00	31.11	0.00	6
31	1	0	91.17	0.00	0.00	52.13	0.00	0.00	7
32	1	0	27.57	0.00	0.00	15.77	0.00	0.00	7
33	1	1	0.00	96.85	0.00	0.00	55.37	0.00	7
34	1	1	0.00	29.29	0.00	0.00	16.75	0.00	7
35	1	2	0.00	0.00	102.75	0.00	0.00	58.85	7
36	1	2	0.00	0.00	31.08	0.00	0.00	17.80	7
37	3	0	88.30	93.80	99.52	50.49	53.63	57.00	7
38	3	0	26.41	28.05	29.76	15.10	16.04	17.05	7
39	3	0	100.77	107.05	113.58	57.62	61.21	65.05	7
40	3	0	37.95	40.32	42.78	21.70	23.05	24.50	7
41	3	0	21.32	22.65	24.03	12.19	12.95	13.76	7
42	1	2	0.00	0.00	25.23	0.00	0.00	22.41	8
43	1	2	0.00	0.00	61.89	0.00	0.00	54.98	8
44	1	2	0.00	0.00	47.55	0.00	0.00	42.24	8
45	1	2	0.00	0.00	35.33	0.00	0.00	31.38	8
46	1	0	86.10	0.00	0.00	33.73	0.00	0.00	9
47	1	0	60.66	0.00	0.00	23.76	0.00	0.00	9
48	1	1	0.00	12.07	0.00	0.00	10.65	0.00	9
49	1	1	0.00	8.50	0.00	0.00	7.50	0.00	9
50	1	2	0.00	0.00	51.49	0.00	0.00	37.64	9
51	1	2	0.00	0.00	36.27	0.00	0.00	26.51	9
52	3	0	56.97	7.99	34.07	22.32	7.05	24.90	9
53	3	0	95.06	13.33	56.84	37.24	11.76	41.55	9
54	3	0	29.62	4.15	17.71	11.61	3.66	12.95	9
55	3	0	78.47	11.00	46.92	30.74	9.71	34.30	9
56	3	0	78.11	10.95	46.71	30.60	9.66	34.14	9
57	1	0	45.17	0.00	0.00	30.35	0.00	0.00	11
58	1	0	67.42	0.00	0.00	45.30	0.00	0.00	11
59	1	0	9.01	0.00	0.00	6.05	0.00	0.00	11
60	1	0	6.41	0.00	0.00	4.30	0.00	0.00	11
61	1	2	0.00	0.00	38.01	0.00	0.00	17.89	12
62	1	2	0.00	0.00	55.80	0.00	0.00	26.26	12
63	1	2	0.00	0.00	66.89	0.00	0.00	31.48	12
64	1	2	0.00	0.00	9.30	0.00	0.00	4.38	12
			1175.00	1039.00	1252.00	616.00	665.00	821.00	

Out phase arrangement post application of Algorithm 1

Sl.No	**Phase**	**Seq**	P_a	P_b	P_c	Q_a	Q_b	Q_c	**Bus**
1	1	0	1.80	0.00	0.00	1.06	0.00	0.00	2
2	1	0	1.91	0.00	0.00	1.12	0.00	0.00	2
3	1	1	0.00	6.97	0.00	0.00	4.02	0.00	2
4	1	1	0.00	7.42	0.00	0.00	4.27	0.00	2
5	1	2	0.00	0.00	12.36	0.00	0.00	7.19	2
6	1	2	0.00	0.00	13.15	0.00	0.00	7.64	2
7	3	0	0.70	2.71	4.81	0.41	1.56	2.80	2
8	3	0	1.72	6.68	11.85	1.01	3.85	6.89	2
9	3	0	1.66	6.44	11.42	0.98	3.71	6.64	2
10	3	0	0.41	1.60	2.83	0.24	0.92	1.65	2
11	3	0	0.30	1.17	2.07	0.18	0.67	1.21	2
12	1	0	22.06	0.00	0.00	15.17	0.00	0.00	4
13	1	0	42.49	0.00	0.00	29.21	0.00	0.00	4
14	1	1	0.00	16.55	0.00	0.00	12.41	0.00	4
15	1	1	0.00	31.87	0.00	0.00	23.90	0.00	4
16	1	2	0.00	0.00	16.55	0.00	0.00	12.41	4
17	1	2	0.00	0.00	31.87	0.00	0.00	23.90	4
18	3	0	15.07	11.30	11.30	10.36	8.48	8.48	4
19	3	0	25.91	19.43	19.43	17.81	14.58	14.58	4
20	3	0	9.91	7.43	7.43	6.81	5.57	5.57	4
21	3	0	33.26	24.95	24.95	22.87	18.71	18.71	4
22	3	0	11.29	8.47	8.47	7.76	6.35	6.35	4
23	1	2	0.00	0.00	28.15	0.00	0.00	20.70	5
24	1	1	0.00	38.90	0.00	0.00	28.60	0.00	5
25	1	1	0.00	49.57	0.00	0.00	36.45	0.00	5
26	1	2	0.00	0.00	53.38	0.00	0.00	39.25	5
27	1	1	0.00	115.19	0.00	0.00	66.11	0.00	6
28	1	1	0.00	29.18	0.00	0.00	16.75	0.00	6
29	1	2	0.00	0.00	31.43	0.00	0.00	18.04	6
30	1	2	0.00	0.00	54.21	0.00	0.00	31.11	6
31	1	0	91.17	0.00	0.00	52.13	0.00	0.00	7
32	1	0	27.57	0.00	0.00	15.77	0.00	0.00	7
33	1	1	0.00	96.85	0.00	0.00	55.37	0.00	7

Sl.No	Phase	Seq	P_a	P_b	P_c	Q_a	Q_b	Q_c	Bus
34	1	1	0.00	29.29	0.00	0.00	16.75	0.00	7
35	1	2	0.00	0.00	102.75	0.00	0.00	58.85	7
36	1	2	0.00	0.00	31.08	0.00	0.00	17.80	7
37	3	0	88.30	93.80	99.52	50.49	53.63	57.00	7
38	3	0	26.41	28.05	29.76	15.10	16.04	17.05	7
39	3	0	100.77	107.05	113.58	57.62	61.21	65.05	7
40	3	0	37.95	40.32	42.78	21.70	23.05	24.50	7
41	3	0	21.32	22.65	24.03	12.19	12.95	13.76	7
42	1	0	25.23	0.00	0.00	22.41	0.00	0.00	8
43	1	2	0.00	0.00	61.89	0.00	0.00	54.98	8
44	1	1	0.00	47.55	0.00	0.00	42.24	0.00	8
45	1	0	35.33	0.00	0.00	31.38	0.00	0.00	8
46	1	1	0.00	86.10	0.00	0.00	33.73	0.00	9
47	1	1	0.00	60.66	0.00	0.00	23.76	0.00	9
48	1	1	0.00	12.07	0.00	0.00	10.65	0.00	9
49	1	1	0.00	8.50	0.00	0.00	7.50	0.00	9
50	1	2	0.00	0.00	51.49	0.00	0.00	37.64	9
51	1	2	0.00	0.00	36.27	0.00	0.00	26.51	9
52	3	0	56.97	7.99	34.07	22.32	7.05	24.90	9
53	3	0	95.06	13.33	56.84	37.24	11.76	41.55	9
54	3	0	29.62	4.15	17.71	11.61	3.66	12.95	9
55	3	0	78.47	11.00	46.92	30.74	9.71	34.30	9
56	3	0	78.11	10.95	46.71	30.60	9.66	34.14	9
57	1	0	45.17	0.00	0.00	30.35	0.00	0.00	11
58	1	0	67.42	0.00	0.00	45.30	0.00	0.00	11
59	1	0	9.01	0.00	0.00	6.05	0.00	0.00	11
60	1	0	6.41	0.00	0.00	4.30	0.00	0.00	11
61	1	2	0.00	0.00	38.01	0.00	0.00	17.89	12
62	1	2	0.00	0.00	55.80	0.00	0.00	26.26	12
63	1	2	0.00	0.00	66.89	0.00	0.00	31.48	12
64	1	2	0.00	0.00	9.30	0.00	0.00	4.38	12
			1088.80	1066.15	1311.05	612.29	655.64	834.07	

Out phase arrangement post application of Algorithm 2

Sl.No	**Phase**	**Seq**	P_a	P_b	P_c	Q_a	Q_b	Q_c	**Bus**
1	1	0	1.80	0.00	0.00	1.06	0.00	0.00	2
2	1	0	1.91	0.00	0.00	1.12	0.00	0.00	2
3	1	1	0.00	6.97	0.00	0.00	4.02	0.00	2
4	1	1	0.00	7.42	0.00	0.00	4.27	0.00	2
5	1	2	0.00	0.00	12.36	0.00	0.00	7.19	2
6	1	2	0.00	0.00	13.15	0.00	0.00	7.64	2
8	3	1	6.68	11.85	1.72	3.85	6.89	1.01	2
9	3	2	11.42	1.66	6.44	6.64	0.98	3.71	2
10	3	0	0.41	1.60	2.83	0.24	0.92	1.65	2
11	3	0	0.30	1.17	2.07	0.18	0.67	1.21	2
12	1	0	22.06	0.00	0.00	15.17	0.00	0.00	4
13	1	0	42.49	0.00	0.00	29.21	0.00	0.00	4
14	1	1	0.00	16.55	0.00	0.00	12.41	0.00	4
15	1	1	0.00	31.87	0.00	0.00	23.90	0.00	4
16	1	2	0.00	0.00	16.55	0.00	0.00	12.41	4
17	1	2	0.00	0.00	31.87	0.00	0.00	23.90	4
18	3	0	15.07	11.30	11.30	10.36	8.48	8.48	4
19	3	0	25.91	19.43	19.43	17.81	14.58	14.58	4
20	3	0	9.91	7.43	7.43	6.81	5.57	5.57	4
21	3	0	33.26	24.95	24.95	22.87	18.71	18.71	4
22	3	0	11.29	8.47	8.47	7.76	6.35	6.35	4
23	1	2	0.00	0.00	28.15	0.00	0.00	20.70	5
24	1	1	0.00	38.90	0.00	0.00	28.60	0.00	5
25	1	1	0.00	49.57	0.00	0.00	36.45	0.00	5
26	1	2	0.00	0.00	53.38	0.00	0.00	39.25	5
27	1	1	0.00	115.19	0.00	0.00	66.11	0.00	6
28	1	1	0.00	29.18	0.00	0.00	16.75	0.00	6
29	1	2	0.00	0.00	31.43	0.00	0.00	18.04	6
30	1	2	0.00	0.00	54.21	0.00	0.00	31.11	6
31	1	0	91.17	0.00	0.00	52.13	0.00	0.00	7
32	1	0	27.57	0.00	0.00	15.77	0.00	0.00	7
33	1	1	0.00	96.85	0.00	0.00	55.37	0.00	7
34	1	1	0.00	29.29	0.00	0.00	16.75	0.00	7

Sl.No	**Phase**	**Seq**	P_a	P_b	P_c	Q_a	Q_b	Q_c	**Bus**
35	1	2	0.00	0.00	102.75	0.00	0.00	58.85	7
36	1	2	0.00	0.00	31.08	0.00	0.00	17.80	7
37	3	0	88.30	93.80	99.52	50.49	53.63	57.00	7
38	3	0	26.41	28.05	29.76	15.10	16.04	17.05	7
39	3	0	100.77	107.05	113.58	57.62	61.21	65.05	7
40	3	0	37.95	40.32	42.78	21.70	23.05	24.50	7
41	3	0	21.32	22.65	24.03	12.19	12.95	13.76	7
42	1	0	25.23	0.00	0.00	22.41	0.00	0.00	8
43	1	2	0.00	0.00	61.89	0.00	0.00	54.98	8
44	1	1	0.00	47.55	0.00	0.00	42.24	0.00	8
45	1	0	35.33	0.00	0.00	31.38	0.00	0.00	8
46	1	1	0.00	86.10	0.00	0.00	33.73	0.00	9
47	1	1	0.00	60.66	0.00	0.00	23.76	0.00	9
48	1	1	0.00	12.07	0.00	0.00	10.65	0.00	9
49	1	1	0.00	8.50	0.00	0.00	7.50	0.00	9
50	1	2	0.00	0.00	51.49	0.00	0.00	37.64	9
51	1	2	0.00	0.00	36.27	0.00	0.00	26.51	9
52	3	0	56.97	7.99	34.07	22.32	7.05	24.90	9
53	3	2	56.84	95.06	13.33	41.55	37.24	11.76	9
54	3	1	4.15	17.71	29.62	3.66	12.95	11.61	9
55	3	1	11.00	46.92	78.47	9.71	34.30	30.74	9
56	3	0	78.11	10.95	46.71	30.60	9.66	34.14	9
57	1	0	45.17	0.00	0.00	30.35	0.00	0.00	11
58	1	0	67.42	0.00	0.00	45.30	0.00	0.00	11
59	1	0	9.01	0.00	0.00	6.05	0.00	0.00	11
60	1	0	6.41	0.00	0.00	4.30	0.00	0.00	11
61	1	2	0.00	0.00	38.01	0.00	0.00	17.89	12
62	1	2	0.00	0.00	55.80	0.00	0.00	26.26	12
63	1	2	0.00	0.00	66.89	0.00	0.00	31.48	12
64	1	2	0.00	0.00	9.30	0.00	0.00	4.38	12
			971.66	1195.03	1291.09	595.72	713.74	787.78	

Out phase arrangement post application of Algorithm 3

Sl.No	Phase	Seq	P_a	P_b	P_c	Q_a	Q_b	Q_c	Bus
1	1	0	1.80	0.00	0.00	1.06	0.00	0.00	2
2	1	0	1.91	0.00	0.00	1.12	0.00	0.00	2
3	1	0	6.97	0.00	0.00	4.02	0.00	0.00	2
4	1	0	7.42	0.00	0.00	4.27	0.00	0.00	2
5	1	2	0.00	0.00	12.36	0.00	0.00	7.19	2
6	1	2	0.00	0.00	13.15	0.00	0.00	7.64	2
7	3	0	0.70	2.71	4.81	0.41	1.56	2.80	2
8	3	1	6.68	11.85	1.72	3.85	6.89	1.01	2
9	3	2	11.42	1.66	6.44	6.64	0.98	3.71	2
10	3	0	0.41	1.60	2.83	0.24	0.92	1.65	2
11	3	0	0.30	1.17	2.07	0.18	0.67	1.21	2
12	1	0	22.06	0.00	0.00	15.17	0.00	0.00	4
13	1	0	42.49	0.00	0.00	29.21	0.00	0.00	4
14	1	1	0.00	16.55	0.00	0.00	12.41	0.00	4
15	1	1	0.00	31.87	0.00	0.00	23.90	0.00	4
16	1	2	0.00	0.00	16.55	0.00	0.00	12.41	4
17	1	2	0.00	0.00	31.87	0.00	0.00	23.90	4
18	3	0	15.07	11.30	11.30	10.36	8.48	8.48	4
19	3	0	25.91	19.43	19.43	17.81	14.58	14.58	4
20	3	0	9.91	7.43	7.43	6.81	5.57	5.57	4
21	3	0	33.26	24.95	24.95	22.87	18.71	18.71	4
22	3	0	11.29	8.47	8.47	7.76	6.35	6.35	4
23	1	2	0.00	0.00	28.15	0.00	0.00	20.70	5
24	1	1	0.00	38.90	0.00	0.00	28.60	0.00	5
25	1	1	0.00	49.57	0.00	0.00	36.45	0.00	5
26	1	2	0.00	0.00	53.38	0.00	0.00	39.25	5
27	1	1	0.00	115.19	0.00	0.00	66.11	0.00	6
28	1	1	0.00	29.18	0.00	0.00	16.75	0.00	6
29	1	2	0.00	0.00	31.43	0.00	0.00	18.04	6
30	1	2	0.00	0.00	54.21	0.00	0.00	31.11	6
31	1	0	91.17	0.00	0.00	52.13	0.00	0.00	7
32	1	0	27.57	0.00	0.00	15.77	0.00	0.00	7
33	1	1	0.00	96.85	0.00	0.00	55.37	0.00	7

Sl.No	**Phase**	**Seq**	**P_a**	**P_b**	**P_c**	**Q_a**	**Q_b**	**Q_c**	**Bus**
34	1	1	0.00	29.29	0.00	0.00	16.75	0.00	7
35	1	2	0.00	0.00	102.75	0.00	0.00	58.85	7
36	1	2	0.00	0.00	31.08	0.00	0.00	17.80	7
37	3	0	88.30	93.80	99.52	50.49	53.63	57.00	7
38	3	0	26.41	28.05	29.76	15.10	16.04	17.05	7
39	3	0	100.77	107.05	113.58	57.62	61.21	65.05	7
40	3	0	37.95	40.32	42.78	21.70	23.05	24.50	7
41	3	0	21.32	22.65	24.03	12.19	12.95	13.76	7
42	1	0	25.23	0.00	0.00	22.41	0.00	0.00	8
43	1	2	0.00	0.00	61.89	0.00	0.00	54.98	8
44	1	1	0.00	47.55	0.00	0.00	42.24	0.00	8
45	1	0	35.33	0.00	0.00	31.38	0.00	0.00	8
46	1	0	86.10	0.00	0.00	33.73	0.00	0.00	9
47	1	1	0.00	60.66	0.00	0.00	23.76	0.00	9
48	1	1	0.00	12.07	0.00	0.00	10.65	0.00	9
49	1	1	0.00	8.50	0.00	0.00	7.50	0.00	9
50	1	2	0.00	0.00	51.49	0.00	0.00	37.64	9
51	1	2	0.00	0.00	36.27	0.00	0.00	26.51	9
52	3	0	56.97	7.99	34.07	22.32	7.05	24.90	9
53	3	2	56.84	95.06	13.33	41.55	37.24	11.76	9
54	3	1	4.15	17.71	29.62	3.66	12.95	11.61	9
55	3	1	11.00	46.92	78.47	9.71	34.30	30.74	9
56	3	0	78.11	10.95	46.71	30.60	9.66	34.14	9
57	1	0	45.17	0.00	0.00	30.35	0.00	0.00	11
58	1	0	67.42	0.00	0.00	45.30	0.00	0.00	11
59	1	0	9.01	0.00	0.00	6.05	0.00	0.00	11
60	1	0	6.41	0.00	0.00	4.30	0.00	0.00	11
61	1	2	0.00	0.00	38.01	0.00	0.00	17.89	12
62	1	2	0.00	0.00	55.80	0.00	0.00	26.26	12
63	1	2	0.00	0.00	66.89	0.00	0.00	31.48	12
64	1	2	0.00	0.00	9.30	0.00	0.00	4.38	12
			1072.86	1097.24	1295.90	638.15	673.28	790.57	

Out phase arrangement post application of Algorithm 4

Sl.No	Phase	Seq	P_a	P_b	P_c	Q_a	Q_b	Q_c	Bus
1	1	0	1.80	0.00	0.00	1.06	0.00	0.00	2
2	1	0	1.91	0.00	0.00	1.12	0.00	0.00	2
3	1	1	0.00	6.97	0.00	0.00	4.02	0.00	2
4	1	1	0.00	7.42	0.00	0.00	4.27	0.00	2
5	1	2	0.00	0.00	12.36	0.00	0.00	7.19	2
6	1	2	0.00	0.00	13.15	0.00	0.00	7.64	2
7	3	0	0.70	2.71	4.81	0.41	1.56	2.80	2
8	3	0	1.72	6.68	11.85	1.01	3.85	6.89	2
9	3	0	1.66	6.44	11.42	0.98	3.71	6.64	2
10	3	0	0.41	1.60	2.83	0.24	0.92	1.65	2
11	3	0	0.30	1.17	2.07	0.18	0.67	1.21	2
12	1	0	22.06	0.00	0.00	15.17	0.00	0.00	4
13	1	0	42.49	0.00	0.00	29.21	0.00	0.00	4
14	1	1	0.00	16.55	0.00	0.00	12.41	0.00	4
15	1	1	0.00	31.87	0.00	0.00	23.90	0.00	4
16	1	2	0.00	0.00	16.55	0.00	0.00	12.41	4
17	1	2	0.00	0.00	31.87	0.00	0.00	23.90	4
18	3	0	15.07	11.30	11.30	10.36	8.48	8.48	4
19	3	0	25.91	19.43	19.43	17.81	14.58	14.58	4
20	3	0	9.91	7.43	7.43	6.81	5.57	5.57	4
21	3	0	33.26	24.95	24.95	22.87	18.71	18.71	4
22	3	0	11.29	8.47	8.47	7.76	6.35	6.35	4
23	1	2	0.00	0.00	28.15	0.00	0.00	20.70	5
24	1	1	0.00	38.90	0.00	0.00	28.60	0.00	5
25	1	1	0.00	49.57	0.00	0.00	36.45	0.00	5
26	1	2	0.00	0.00	53.38	0.00	0.00	39.25	5
27	1	1	0.00	115.19	0.00	0.00	66.11	0.00	6
28	1	1	0.00	29.18	0.00	0.00	16.75	0.00	6
29	1	2	0.00	0.00	31.43	0.00	0.00	18.04	6
30	1	2	0.00	0.00	54.21	0.00	0.00	31.11	6
31	1	0	91.17	0.00	0.00	52.13	0.00	0.00	7
32	1	0	27.57	0.00	0.00	15.77	0.00	0.00	7
33	1	1	0.00	96.85	0.00	0.00	55.37	0.00	7

Sl.No	Phase	Seq	P_a	P_b	P_c	Q_a	Q_b	Q_c	Bus
34	1	2	0.00	0.00	29.29	0.00	0.00	16.75	7
35	1	2	0.00	0.00	102.75	0.00	0.00	58.85	7
36	1	2	0.00	0.00	31.08	0.00	0.00	17.80	7
37	3	0	88.30	93.80	99.52	50.49	53.63	57.00	7
38	3	0	26.41	28.05	29.76	15.10	16.04	17.05	7
39	3	0	100.77	107.05	113.58	57.62	61.21	65.05	7
40	3	0	37.95	40.32	42.78	21.70	23.05	24.50	7
41	3	0	21.32	22.65	24.03	12.19	12.95	13.76	7
42	1	0	25.23	0.00	0.00	22.41	0.00	0.00	8
43	1	1	0.00	61.89	0.00	0.00	54.98	0.00	8
44	1	1	0.00	47.55	0.00	0.00	42.24	0.00	8
45	1	1	0.00	35.33	0.00	0.00	31.38	0.00	8
46	1	1	0.00	86.10	0.00	0.00	33.73	0.00	9
47	1	1	0.00	60.66	0.00	0.00	23.76	0.00	9
48	1	1	0.00	12.07	0.00	0.00	10.65	0.00	9
49	1	1	0.00	8.50	0.00	0.00	7.50	0.00	9
50	1	1	0.00	51.49	0.00	0.00	37.64	0.00	9
51	1	1	0.00	36.27	0.00	0.00	26.51	0.00	9
52	3	0	56.97	7.99	34.07	22.32	7.05	24.90	9
53	3	0	95.06	13.33	56.84	37.24	11.76	41.55	9
54	3	0	29.62	4.15	17.71	11.61	3.66	12.95	9
55	3	0	78.47	11.00	46.92	30.74	9.71	34.30	9
56	3	0	78.11	10.95	46.71	30.60	9.66	34.14	9
57	1	0	45.17	0.00	0.00	30.35	0.00	0.00	11
58	1	0	67.42	0.00	0.00	45.30	0.00	0.00	11
59	1	0	9.01	0.00	0.00	6.05	0.00	0.00	11
60	1	0	6.41	0.00	0.00	4.30	0.00	0.00	11
61	1	2	0.00	0.00	38.01	0.00	0.00	17.89	12
62	1	2	0.00	0.00	55.80	0.00	0.00	26.26	12
63	1	2	0.00	0.00	66.89	0.00	0.00	31.48	12
64	1	2	0.00	0.00	9.30	0.00	0.00	4.38	12
			1053.47	1221.83	1190.70	580.91	789.40	731.69	

Out phase arrangement post application of Algorithm 5

Sl.No	Phase	Seq	P_a	P_b	P_c	Q_a	Q_b	Q_c	Bus
1	1	0	1.80	0.00	0.00	1.06	0.00	0.00	2
2	1	0	1.91	0.00	0.00	1.12	0.00	0.00	2
3	1	1	0.00	6.97	0.00	0.00	4.02	0.00	2
4	1	1	0.00	7.42	0.00	0.00	4.27	0.00	2
5	1	2	0.00	0.00	12.36	0.00	0.00	7.19	2
6	1	2	0.00	0.00	13.15	0.00	0.00	7.64	2
7	3	2	4.81	0.70	2.71	2.80	0.41	1.56	2
8	3	2	11.85	1.72	6.68	6.89	1.01	3.85	2
9	3	2	11.42	1.66	6.44	6.64	0.98	3.71	2
10	3	2	2.83	0.41	1.60	1.65	0.24	0.92	2
11	3	2	2.07	0.30	1.17	1.21	0.18	0.67	2
12	1	0	22.06	0.00	0.00	15.17	0.00	0.00	4
13	1	0	42.49	0.00	0.00	29.21	0.00	0.00	4
14	1	1	0.00	16.55	0.00	0.00	12.41	0.00	4
15	1	1	0.00	31.87	0.00	0.00	23.90	0.00	4
16	1	2	0.00	0.00	16.55	0.00	0.00	12.41	4
17	1	2	0.00	0.00	31.87	0.00	0.00	23.90	4
18	3	0	15.07	11.30	11.30	10.36	8.48	8.48	4
19	3	0	25.91	19.43	19.43	17.81	14.58	14.58	4
20	3	0	9.91	7.43	7.43	6.81	5.57	5.57	4
21	3	0	33.26	24.95	24.95	22.87	18.71	18.71	4
22	3	0	11.29	8.47	8.47	7.76	6.35	6.35	4
23	1	2	0.00	0.00	28.15	0.00	0.00	20.70	5
24	1	1	0.00	38.90	0.00	0.00	28.60	0.00	5
25	1	1	0.00	49.57	0.00	0.00	36.45	0.00	5
26	1	2	0.00	0.00	53.38	0.00	0.00	39.25	5
27	1	1	0.00	115.19	0.00	0.00	66.11	0.00	6
28	1	1	0.00	29.18	0.00	0.00	16.75	0.00	6
29	1	2	0.00	0.00	31.43	0.00	0.00	18.04	6
30	1	2	0.00	0.00	54.21	0.00	0.00	31.11	6
31	1	0	91.17	0.00	0.00	52.13	0.00	0.00	7
32	1	0	27.57	0.00	0.00	15.77	0.00	0.00	7
33	1	1	0.00	96.85	0.00	0.00	55.37	0.00	7

Sl.No	Phase	Seq	P_a	P_b	P_c	Q_a	Q_b	Q_c	Bus
34	1	1	0.00	29.29	0.00	0.00	16.75	0.00	7
35	1	1	0.00	102.75	0.00	0.00	58.85	0.00	7
36	1	2	0.00	0.00	31.08	0.00	0.00	17.80	7
37	3	0	88.30	93.80	99.52	50.49	53.63	57.00	7
38	3	0	26.41	28.05	29.76	15.10	16.04	17.05	7
39	3	0	100.77	107.05	113.58	57.62	61.21	65.05	7
40	3	0	37.95	40.32	42.78	21.70	23.05	24.50	7
41	3	0	21.32	22.65	24.03	12.19	12.95	13.76	7
42	1	2	0.00	0.00	25.23	0.00	0.00	22.41	8
43	1	1	0.00	61.89	0.00	0.00	54.98	0.00	8
44	1	0	47.55	0.00	0.00	42.24	0.00	0.00	8
45	1	2	0.00	0.00	35.33	0.00	0.00	31.38	8
46	1	0	86.10	0.00	0.00	33.73	0.00	0.00	9
47	1	1	0.00	60.66	0.00	0.00	23.76	0.00	9
48	1	1	0.00	12.07	0.00	0.00	10.65	0.00	9
49	1	1	0.00	8.50	0.00	0.00	7.50	0.00	9
50	1	2	0.00	0.00	51.49	0.00	0.00	37.64	9
51	1	2	0.00	0.00	36.27	0.00	0.00	26.51	9
52	3	0	56.97	7.99	34.07	22.32	7.05	24.90	9
53	3	2	56.84	95.06	13.33	41.55	37.24	11.76	9
54	3	1	4.15	17.71	29.62	3.66	12.95	11.61	9
55	3	1	11.00	46.92	78.47	9.71	34.30	30.74	9
56	3	0	78.11	10.95	46.71	30.60	9.66	34.14	9
57	1	0	45.17	0.00	0.00	30.35	0.00	0.00	11
58	1	0	67.42	0.00	0.00	45.30	0.00	0.00	11
59	1	0	9.01	0.00	0.00	6.05	0.00	0.00	11
60	1	0	6.41	0.00	0.00	4.30	0.00	0.00	11
61	1	2	0.00	0.00	38.01	0.00	0.00	17.89	12
62	1	2	0.00	0.00	55.80	0.00	0.00	26.26	12
63	1	2	0.00	0.00	66.89	0.00	0.00	31.48	12
64	1	2	0.00	0.00	9.30	0.00	0.00	4.38	12
			1058.93	1214.54	1192.54	626.16	744.96	730.88	

Out phase arrangement post application of Algorithm 6

Sl.No	**Phase**	**Seq**	**P_a**	**P_b**	**P_c**	**Q_a**	**Q_b**	**Q_c**	**Bus**
1	1	0	1.80	0.00	0.00	1.06	0.00	0.00	2
2	1	0	1.91	0.00	0.00	1.12	0.00	0.00	2
3	1	2	0.00	0.00	6.97	0.00	0.00	4.02	2
4	1	2	0.00	0.00	7.42	0.00	0.00	4.27	2
5	1	2	0.00	0.00	12.36	0.00	0.00	7.19	2
6	1	2	0.00	0.00	13.15	0.00	0.00	7.64	2
7	3	0	0.70	2.71	4.81	0.41	1.56	2.80	2
8	3	1	6.68	11.85	1.72	3.85	6.89	1.01	2
9	3	2	11.42	1.66	6.44	6.64	0.98	3.71	2
10	3	0	0.41	1.60	2.83	0.24	0.92	1.65	2
11	3	0	0.30	1.17	2.07	0.18	0.67	1.21	2
12	1	0	22.06	0.00	0.00	15.17	0.00	0.00	4
13	1	0	42.49	0.00	0.00	29.21	0.00	0.00	4
14	1	1	0.00	16.55	0.00	0.00	12.41	0.00	4
15	1	1	0.00	31.87	0.00	0.00	23.90	0.00	4
16	1	2	0.00	0.00	16.55	0.00	0.00	12.41	4
17	1	2	0.00	0.00	31.87	0.00	0.00	23.90	4
18	3	0	15.07	11.30	11.30	10.36	8.48	8.48	4
19	3	0	25.91	19.43	19.43	17.81	14.58	14.58	4
20	3	0	9.91	7.43	7.43	6.81	5.57	5.57	4
21	3	0	33.26	24.95	24.95	22.87	18.71	18.71	4
22	3	0	11.29	8.47	8.47	7.76	6.35	6.35	4
23	1	0	28.15	0.00	0.00	20.70	0.00	0.00	5
24	1	0	38.90	0.00	0.00	28.60	0.00	0.00	5
25	1	0	49.57	0.00	0.00	36.45	0.00	0.00	5
26	1	0	53.38	0.00	0.00	39.25	0.00	0.00	5
27	1	0	0.00	115.19	0.00	0.00	66.11	0.00	6
28	1	0	0.00	29.18	0.00	0.00	16.75	0.00	6
29	1	0	0.00	31.43	0.00	0.00	18.04	0.00	6
30	1	0	0.00	54.21	0.00	0.00	31.11	0.00	6
31	1	0	91.17	0.00	0.00	52.13	0.00	0.00	7
32	1	0	27.57	0.00	0.00	15.77	0.00	0.00	7
33	1	1	0.00	96.85	0.00	0.00	55.37	0.00	7

Sl.No	**Phase**	**Seq**	**P_a**	**P_b**	**P_c**	**Q_a**	**Q_b**	**Q_c**	**Bus**
34	1	1	0.00	29.29	0.00	0.00	16.75	0.00	7
35	1	2	0.00	0.00	102.75	0.00	0.00	58.85	7
36	1	1	0.00	31.08	0.00	0.00	17.80	0.00	7
37	3	0	88.30	93.80	99.52	50.49	53.63	57.00	7
38	3	0	26.41	28.05	29.76	15.10	16.04	17.05	7
39	3	0	100.77	107.05	113.58	57.62	61.21	65.05	7
40	3	0	37.95	40.32	42.78	21.70	23.05	24.50	7
41	3	0	21.32	22.65	24.03	12.19	12.95	13.76	7
42	1	0	25.23	0.00	0.00	22.41	0.00	0.00	8
43	1	2	0.00	0.00	61.89	0.00	0.00	54.98	8
44	1	1	0.00	47.55	0.00	0.00	42.24	0.00	8
45	1	0	35.33	0.00	0.00	31.38	0.00	0.00	8
46	1	0	86.10	0.00	0.00	33.73	0.00	0.00	9
47	1	1	0.00	60.66	0.00	0.00	23.76	0.00	9
48	1	1	0.00	12.07	0.00	0.00	10.65	0.00	9
49	1	1	0.00	8.50	0.00	0.00	7.50	0.00	9
50	1	2	0.00	0.00	51.49	0.00	0.00	37.64	9
51	1	2	0.00	0.00	36.27	0.00	0.00	26.51	9
52	3	0	56.97	7.99	34.07	22.32	7.05	24.90	9
53	3	2	56.84	95.06	13.33	41.55	37.24	11.76	9
54	3	1	4.15	17.71	29.62	3.66	12.95	11.61	9
55	3	1	11.00	46.92	78.47	9.71	34.30	30.74	9
56	3	0	78.11	10.95	46.71	30.60	9.66	34.14	9
57	1	0	45.17	0.00	0.00	30.35	0.00	0.00	11
58	1	0	67.42	0.00	0.00	45.30	0.00	0.00	11
59	1	0	9.01	0.00	0.00	6.05	0.00	0.00	11
60	1	0	6.41	0.00	0.00	4.30	0.00	0.00	11
61	1	2	0.00	0.00	38.01	0.00	0.00	17.89	12
62	1	2	0.00	0.00	55.80	0.00	0.00	26.26	12
63	1	2	0.00	0.00	66.89	0.00	0.00	31.48	12
64	1	2	0.00	0.00	9.30	0.00	0.00	4.38	12
			1228.46	1125.48	1112.06	754.86	675.17	671.97	

APPENDIX II

TYPICAL SYSTEM AT MYSURU

Phase arrangement before balancing

Sl.No	Phase	Seq	P_a	P_b	P_c	Q_a	Q_b	Q_c	Bus
2	1	2	0.00	0.00	0.02	0.00	0.00	0.02	5
3	1	2	0.00	0.00	0.02	0.00	0.00	0.00	5
4	1	2	0.00	0.00	0.01	0.00	0.00	0.00	5
5	1	1	0.00	0.04	0.00	0.00	0.01	0.00	6
6	1	1	0.00	0.02	0.00	0.00	0.01	0.00	6
7	1	1	0.00	0.00	0.00	0.00	0.00	0.00	6
8	1	1	0.00	0.00	0.00	0.00	0.00	0.00	6
9	1	1	0.00	0.02	0.00	0.00	0.00	0.00	6
10	1	1	0.00	0.03	0.00	0.00	0.02	0.00	6
11	1	0	0.01	0.00	0.00	0.00	0.00	0.00	8
12	1	0	0.02	0.00	0.00	0.00	0.00	0.00	8
13	1	0	0.01	0.00	0.00	0.00	0.00	0.00	8
14	1	0	0.02	0.00	0.00	0.00	0.00	0.00	8
15	1	0	0.00	0.00	0.00	0.00	0.00	0.00	8
16	1	0	0.02	0.00	0.00	0.01	0.00	0.00	8
17	1	0	0.01	0.00	0.00	0.00	0.00	0.00	8
18	1	0	0.01	0.00	0.00	0.00	0.00	0.00	8
19	1	0	0.00	0.00	0.00	0.00	0.00	0.00	8
20	1	1	0.00	0.02	0.00	0.00	0.00	0.00	8
21	1	1	0.00	0.01	0.00	0.00	0.00	0.00	8
22	1	1	0.00	0.02	0.00	0.00	0.00	0.00	8
23	1	1	0.00	0.01	0.00	0.00	0.00	0.00	8
24	1	1	0.00	0.02	0.00	0.00	0.01	0.00	8
25	1	1	0.00	0.02	0.00	0.00	0.00	0.00	8
26	1	1	0.00	0.01	0.00	0.00	0.01	0.00	8
27	1	1	0.00	0.02	0.00	0.00	0.00	0.00	8
28	1	1	0.00	0.01	0.00	0.00	0.00	0.00	8
29	1	1	0.00	0.05	0.00	0.00	0.01	0.00	8

Sl.No	Phase	Seq	P_a	P_b	P_c	Q_a	Q_b	Q_c	Bus
30	1	1	0.00	0.04	0.00	0.00	0.02	0.00	8
31	1	2	0.00	0.00	0.02	0.00	0.00	0.01	8
32	1	2	0.00	0.00	0.01	0.00	0.00	0.00	8
33	1	2	0.00	0.00	0.02	0.00	0.00	0.00	8
34	1	0	0.01	0.00	0.00	0.00	0.00	0.00	10
35	1	0	0.00	0.00	0.00	0.00	0.00	0.00	10
36	1	0	0.00	0.00	0.00	0.00	0.00	0.00	10
37	1	0	0.00	0.00	0.00	0.00	0.00	0.00	10
38	1	0	0.01	0.00	0.00	0.02	0.00	0.00	10
39	1	0	0.02	0.00	0.00	0.01	0.00	0.00	10
40	1	0	0.01	0.00	0.00	0.00	0.00	0.00	10
41	1	0	0.00	0.00	0.00	0.00	0.00	0.00	10
42	1	0	0.01	0.00	0.00	0.00	0.00	0.00	10
44	1	0	0.01	0.00	0.00	0.00	0.00	0.00	10
45	1	0	0.02	0.00	0.00	0.00	0.00	0.00	10
46	1	0	0.00	0.00	0.00	0.00	0.00	0.00	10
48	1	1	0.00	0.01	0.00	0.00	0.00	0.00	11
49	1	1	0.00	0.00	0.00	0.00	0.00	0.00	11
50	1	1	0.00	0.00	0.00	0.00	0.00	0.00	11
51	1	1	0.00	0.00	0.00	0.00	0.00	0.00	11
52	1	1	0.00	0.01	0.00	0.00	0.00	0.00	11
53	1	1	0.00	0.00	0.00	0.00	0.00	0.00	11
54	1	1	0.00	0.01	0.00	0.00	0.00	0.00	11
55	1	1	0.00	0.01	0.00	0.00	0.00	0.00	11
56	1	1	0.00	0.00	0.00	0.00	0.00	0.00	11
57	1	1	0.00	0.00	0.00	0.00	0.00	0.00	11
58	1	1	0.00	0.00	0.00	0.00	0.00	0.00	11
59	1	1	0.00	0.01	0.00	0.00	0.00	0.00	11
60	1	1	0.00	0.13	0.00	0.00	0.03	0.00	11
61	1	1	0.00	0.00	0.00	0.00	0.00	0.00	11
62	1	1	0.00	0.02	0.00	0.00	0.01	0.00	11
63	1	1	0.00	0.01	0.00	0.00	0.00	0.00	11
64	1	1	0.00	0.01	0.00	0.00	0.00	0.00	11
65	1	1	0.00	0.02	0.00	0.00	0.00	0.00	12
66	1	1	0.00	0.01	0.00	0.00	0.00	0.00	12
67	1	1	0.00	0.01	0.00	0.00	0.01	0.00	12

Sl.No	**Phase**	**Seq**	**P_a**	**P_b**	**P_c**	**Q_a**	**Q_b**	**Q_c**	**Bus**
68	1	1	0.00	0.01	0.00	0.00	0.00	0.00	12
69	1	**0**	**0.02**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**14**
70	1	0	0.02	0.00	0.00	0.00	0.00	0.00	14
71	1	0	0.01	0.00	0.00	0.00	0.00	0.00	14
72	1	0	0.00	0.00	0.00	0.00	0.00	0.00	14
73	1	0	0.01	0.00	0.00	0.00	0.00	0.00	14
74	1	0	0.00	0.00	0.00	0.00	0.00	0.00	14
75	1	1	0.00	0.01	0.00	0.00	0.01	0.00	14
76	1	1	0.00	0.00	0.00	0.00	0.00	0.00	14
77	1	1	0.00	0.00	0.00	0.00	0.00	0.00	14
78	1	1	0.00	0.02	0.00	0.00	0.01	0.00	14
79	1	1	0.00	0.00	0.00	0.00	0.00	0.00	14
80	1	1	0.00	0.00	0.00	0.00	0.00	0.00	14
81	1	2	0.00	0.00	0.04	0.00	0.00	0.00	14
82	1	2	0.00	0.00	0.01	0.00	0.00	0.00	14
83	1	2	0.00	0.00	0.01	0.00	0.00	0.00	14
84	1	2	0.00	0.00	0.01	0.00	0.00	0.00	14
85	1	2	0.00	0.00	0.02	0.00	0.00	0.00	15
86	1	2	0.00	0.00	0.06	0.00	0.00	0.01	15
87	1	2	0.00	0.00	0.07	0.00	0.00	0.00	15
88	1	2	0.00	0.00	0.02	0.00	0.00	0.00	15
89	1	2	0.00	0.00	0.01	0.00	0.00	0.00	15
90	1	2	0.00	0.00	0.01	0.00	0.00	0.00	15
91	1	2	0.00	0.00	0.02	0.00	0.00	0.00	15
92	1	2	0.00	0.00	0.01	0.00	0.00	0.00	15
93	1	2	0.00	0.00	0.00	0.00	0.00	0.00	15
94	1	2	0.00	0.00	0.00	0.00	0.00	0.00	15
95	1	2	0.00	0.00	0.00	0.00	0.00	0.00	15
96	1	2	0.00	0.00	0.02	0.00	0.00	0.00	15
97	1	2	0.00	0.00	0.01	0.00	0.00	0.00	15
98	1	2	0.00	0.00	0.01	0.00	0.00	0.00	15
99	1	1	0.00	0.01	0.00	0.00	0.00	0.00	16
100	1	1	0.00	0.01	0.00	0.00	0.00	0.00	16
101	1	1	0.00	0.00	0.00	0.00	0.00	0.00	16
102	1	1	0.00	0.01	0.00	0.00	0.00	0.00	16
103	1	1	0.00	0.02	0.00	0.00	0.00	0.00	16

Sl.No	Phase	Seq	P_a	P_b	P_c	Q_a	Q_b	Q_c	Bus
104	1	1	0.00	0.02	0.00	0.00	0.00	0.00	16
105	1	1	0.00	0.03	0.00	0.00	0.01	0.00	16
106	1	1	0.00	0.00	0.00	0.00	0.00	0.00	16
107	1	1	0.00	0.06	0.00	0.00	0.03	0.00	16
108	1	1	0.00	0.01	0.00	0.00	0.00	0.00	16
109	1	1	0.00	0.00	0.00	0.00	0.00	0.00	16
110	1	1	0.00	0.01	0.00	0.00	0.00	0.00	16
111	1	1	0.00	0.00	0.00	0.00	0.00	0.00	16
112	1	1	0.00	0.02	0.00	0.00	0.00	0.00	16
113	1	1	0.00	0.00	0.00	0.00	0.00	0.00	16
			0.25	0.85	0.42	0.06	0.21	0.06	

Phase arrangement after balancing

Sl.No	Phase	Seq	P_a	P_b	P_c	Q_a	Q_b	Q_c	Bus
2	1	2	0.00	0.00	0.02	0.00	0.00	0.02	5
3	1	0	0.02	0.00	0.00	0.00	0.00	0.00	5
4	1	1	0.00	0.01	0.00	0.00	0.00	0.00	5
5	1	1	0.00	0.04	0.00	0.00	0.01	0.00	6
6	1	2	0.00	0.00	0.02	0.00	0.00	0.01	6
7	1	1	0.00	0.00	0.00	0.00	0.00	0.00	6
8	1	1	0.00	0.00	0.00	0.00	0.00	0.00	6
9	1	2	0.00	0.00	0.02	0.00	0.00	0.00	6
10	1	0	0.03	0.00	0.00	0.02	0.00	0.00	6
11	1	0	0.01	0.00	0.00	0.00	0.00	0.00	8
12	1	0	0.02	0.00	0.00	0.00	0.00	0.00	8
13	1	0	0.01	0.00	0.00	0.00	0.00	0.00	8
14	1	0	0.02	0.00	0.00	0.00	0.00	0.00	8
15	1	0	0.00	0.00	0.00	0.00	0.00	0.00	8
16	1	0	0.02	0.00	0.00	0.01	0.00	0.00	8
17	1	0	0.01	0.00	0.00	0.00	0.00	0.00	8
18	1	0	0.01	0.00	0.00	0.00	0.00	0.00	8
19	1	0	0.00	0.00	0.00	0.00	0.00	0.00	8
20	1	2	0.00	0.00	0.02	0.00	0.00	0.00	8

Sl.No	Phase	Seq	P_a	P_b	P_c	Q_a	Q_b	Q_c	Bus
21	1	1	0.00	0.01	0.00	0.00	0.00	0.00	8
22	1	0	0.02	0.00	0.00	0.00	0.00	0.00	8
23	1	2	0.00	0.00	0.01	0.00	0.00	0.00	8
24	1	1	0.00	0.02	0.00	0.00	0.01	0.00	8
25	1	1	0.00	0.02	0.00	0.00	0.00	0.00	8
26	1	1	0.00	0.01	0.00	0.00	0.01	0.00	8
27	1	1	0.00	0.02	0.00	0.00	0.00	0.00	8
28	1	0	0.01	0.00	0.00	0.00	0.00	0.00	8
29	1	2	0.00	0.00	0.05	0.00	0.00	0.01	8
30	1	1	0.00	0.04	0.00	0.00	0.02	0.00	8
31	1	2	0.00	0.00	0.02	0.00	0.00	0.01	8
32	1	2	0.00	0.00	0.01	0.00	0.00	0.00	8
33	1	2	0.00	0.00	0.02	0.00	0.00	0.00	8
34	1	1	0.00	0.01	0.00	0.00	0.00	0.00	10
35	1	0	0.00	0.00	0.00	0.00	0.00	0.00	10
36	1	1	0.00	0.00	0.00	0.00	0.00	0.00	10
37	1	1	0.00	0.00	0.00	0.00	0.00	0.00	10
38	1	2	0.00	0.00	0.01	0.00	0.00	0.02	10
39	1	0	0.02	0.00	0.00	0.01	0.00	0.00	10
40	1	2	0.00	0.00	0.01	0.00	0.00	0.00	10
41	1	0	0.00	0.00	0.00	0.00	0.00	0.00	10
42	1	1	0.00	0.01	0.00	0.00	0.00	0.00	10
44	1	0	0.01	0.00	0.00	0.00	0.00	0.00	10
45	1	1	0.00	0.02	0.00	0.00	0.00	0.00	10
46	1	0	0.00	0.00	0.00	0.00	0.00	0.00	10
48	1	0	0.01	0.00	0.00	0.00	0.00	0.00	11
49	1	1	0.00	0.00	0.00	0.00	0.00	0.00	11
50	1	1	0.00	0.00	0.00	0.00	0.00	0.00	11
51	1	1	0.00	0.00	0.00	0.00	0.00	0.00	11
52	1	0	0.01	0.00	0.00	0.00	0.00	0.00	11
53	1	1	0.00	0.00	0.00	0.00	0.00	0.00	11
54	1	0	0.01	0.00	0.00	0.00	0.00	0.00	11
55	1	0	0.01	0.00	0.00	0.00	0.00	0.00	11
56	1	1	0.00	0.00	0.00	0.00	0.00	0.00	11
57	1	0	0.00	0.00	0.00	0.00	0.00	0.00	11
58	1	0	0.00	0.00	0.00	0.00	0.00	0.00	11

Sl.No	Phase	Seq	P_a	P_b	P_c	Q_a	Q_b	Q_c	Bus
59	1	2	0.00	0.00	0.01	0.00	0.00	0.00	11
60	1	1	0.00	0.13	0.00	0.00	0.03	0.00	11
61	1	2	0.00	0.00	0.00	0.00	0.00	0.00	11
62	1	0	0.02	0.00	0.00	0.01	0.00	0.00	11
63	1	0	0.01	0.00	0.00	0.00	0.00	0.00	11
64	1	0	0.01	0.00	0.00	0.00	0.00	0.00	11
65	1	1	0.00	0.02	0.00	0.00	0.00	0.00	12
66	1	0	0.01	0.00	0.00	0.00	0.00	0.00	12
67	1	2	0.00	0.00	0.01	0.00	0.00	0.01	12
68	1	0	0.01	0.00	0.00	0.00	0.00	0.00	12
69	1	0	0.02	0.00	0.00	0.00	0.00	0.00	14
70	1	0	0.02	0.00	0.00	0.00	0.00	0.00	14
71	1	0	0.01	0.00	0.00	0.00	0.00	0.00	14
72	1	0	0.00	0.00	0.00	0.00	0.00	0.00	14
73	1	0	0.01	0.00	0.00	0.00	0.00	0.00	14
74	1	0	0.00	0.00	0.00	0.00	0.00	0.00	14
75	1	1	0.00	0.01	0.00	0.00	0.01	0.00	14
76	1	1	0.00	0.00	0.00	0.00	0.00	0.00	14
77	1	1	0.00	0.00	0.00	0.00	0.00	0.00	14
78	1	1	0.00	0.02	0.00	0.00	0.01	0.00	14
79	1	1	0.00	0.00	0.00	0.00	0.00	0.00	14
80	1	1	0.00	0.00	0.00	0.00	0.00	0.00	14
81	1	2	0.00	0.00	0.04	0.00	0.00	0.00	14
82	1	1	0.00	0.01	0.00	0.00	0.00	0.00	14
83	1	2	0.00	0.00	0.01	0.00	0.00	0.00	14
84	1	2	0.00	0.00	0.01	0.00	0.00	0.00	14
85	1	0	0.02	0.00	0.00	0.00	0.00	0.00	15
86	1	1	0.00	0.06	0.00	0.00	0.01	0.00	15
87	1	2	0.00	0.00	0.07	0.00	0.00	0.00	15
88	1	1	0.00	0.02	0.00	0.00	0.00	0.00	15
89	1	2	0.00	0.00	0.01	0.00	0.00	0.00	15
90	1	2	0.00	0.00	0.01	0.00	0.00	0.00	15
91	1	0	0.02	0.00	0.00	0.00	0.00	0.00	15
92	1	0	0.01	0.00	0.00	0.00	0.00	0.00	15
93	1	2	0.00	0.00	0.00	0.00	0.00	0.00	15
94	1	0	0.00	0.00	0.00	0.00	0.00	0.00	15

Sl.No	**Phase**	**Seq**	P_a	P_b	P_c	Q_a	Q_b	Q_c	**Bus**
95	1	2	0.00	0.00	0.00	0.00	0.00	0.00	15
96	1	0	0.02	0.00	0.00	0.00	0.00	0.00	15
97	1	0	0.01	0.00	0.00	0.00	0.00	0.00	15
98	1	0	0.01	0.00	0.00	0.00	0.00	0.00	15
99	1	0	0.01	0.00	0.00	0.00	0.00	0.00	16
100	1	2	0.00	0.00	0.01	0.00	0.00	0.00	16
101	1	2	0.00	0.00	0.00	0.00	0.00	0.00	16
102	1	2	0.00	0.00	0.01	0.00	0.00	0.00	16
103	1	0	0.02	0.00	0.00	0.00	0.00	0.00	16
104	1	2	0.00	0.00	0.02	0.00	0.00	0.00	16
105	1	2	0.00	0.00	0.03	0.00	0.00	0.01	16
106	1	1	0.00	0.00	0.00	0.00	0.00	0.00	16
107	1	1	0.00	0.06	0.00	0.00	0.03	0.00	16
108	1	0	0.01	0.00	0.00	0.00	0.00	0.00	16
109	1	1	0.00	0.00	0.00	0.00	0.00	0.00	16
110	1	0	0.01	0.00	0.00	0.00	0.00	0.00	16
111	1	2	0.00	0.00	0.00	0.00	0.00	0.00	16
112	1	0	0.02	0.00	0.00	0.00	0.00	0.00	16
113	1	1	0.00	0.00	0.00	0.00	0.00	0.00	16
			0.52	0.56	0.45	0.09	0.15	0.09	

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