Three-Phase Voltage Regulator Modeling for Forward/ Backward Sweep-Based Distribution Systems Power Flow Algorithms

U. Eminoglu and M. H. Hocaoglu
e-mail: u.eminoglu@gyte.edu.tr, e-mail: hocaoglu@gyte.edu.tr
Gebze Institute of Technology, Department of Electronics Engineering, Kocaeli 41400, TURKEY

Key words: Distribution system, power flow, sweep-based algorithm, voltage regulators

Abstract

This paper describes a new approach for modelling of automatic voltage regulator in the forward/backward sweep-based algorithms for unbalanced radial distribution systems. The automatic voltage regulators (AVRs) are included into the sweep based methods and tested by using two distribution test systems. From the studies, it can be concluded that all results are in agreement, the proposed approach is valid and reliable, and the performance of the algorithms is less affected from the inclusion of regulator modelling.

I. Introduction

Accurate and fast load flow analysis is an important task in power system planning and operational studies. Accordingly there are number of methods in the literature to solve this task. These methods may be listed as Newton-Raphson, Gauss-Seidel and Fast Decoupled load flow algorithms. It has repeatedly been shown that these classical methods may become inefficient in the analysis of distribution systems with high R/X ratios or special network structures [1]. Therefore, there are a number of reported studies in the literature [2-18] specially designed for the solution of power flow problem in radial distribution networks. These methods can be categorized as the Z_{bus} based methods [2-3, 13-14], the Newton Raphson-based methods [5, 7, 9, 10, 15, 16, 17], and the Forward/ Backward sweep-based methods [4, 6, 8, 11, 12, 18].

Since it is the utilities' responsibility to keep the customer voltage within specified tolerances, voltage regulation is an important subject in electrical distribution engineering. One of the performance criteria for a distribution system and the quality of the provided service are the maintenance of satisfactory voltage levels at the customers' premises. However, most equipment and appliances operate satisfactorily over some 'reasonable' range of voltages; hence, certain tolerances are allowed at the customers' end. Thus, it is common practice among utilities to stay within preferred voltage levels and ranges of variations for satisfactory operation of apparatus as set by various standards [19].

One of the most important devices to be utilized for the voltage regulation is the AVRs which can be operated in manual or automatic mode. In the manual mode, the output voltage can be manually raised or lowered on the regulator's control board and it could be modelled as a constant ratio transformer in power flow algorithms. In the automatic mode, the regulator control mechanism adjusts the taps to assure that the voltage being monitored is within certain range. In distribution systems, voltages along the primary feeders are often controlled by voltage regulators. These regulators are generally auto-transformers with individual taps on their windings and must be incorporated into the load flow algorithms. Some distribution system power flow algorithms have been made to incorporate voltage regulator in manual or in automatic mode [6, 13, 16, 17].

Although the Forward/ Backward sweep-based methods are mostly used for the load flow analysis of distribution systems, only a sweep-algorithm, given in [6], incorporated AVRs to the load flow analysis. In the study, AVRs are included into the forward voltage calculation of a particular forward/backward substitution method. However the authors did not model the automatic voltage regulators for the backward voltage calculation as it is not required for their particular algorithm. In distribution load flow analysis, there are number of power flow algorithms which has backward voltage calculation such as; Ratio-Flow method [12], Ladder Network theory [18].

In this paper, the modelling of voltage regulators in the backward/forward sweep-based power flow methods is demonstrated. In section 2, a brief description of these algorithms is provided. The implementation of the automatic voltage regulators into the sweep-based algorithms is given in Section 3. Comparisons are undertaken to verify the approach, and the results are presented in Section 4.

II. Sweep-Based Algorithms

Sweep-based algorithms are based on forward-backward sweep processes using Kirchooff's Laws or making use of the well-known bi-quadratic equation which, for every branch, relates the voltage magnitude at the receiving end to the voltage at the sending end and the branch power flow for solution of ladder networks. Due to its low memory requirements, computational efficiency and robust convergence characteristic, sweep-based methods have gained the most popularity for distribution load flow analysis in recent years.

Forward/Backward Substitution Algorithm

Although the forward/backward substitution algorithm can be extended to solve systems with loops and distributed generation buses, a radial network with only one voltage source is used here to depict the principles of the algorithm. Such a system can be modeled as a tree, in which the root is the voltage source and the branches can be a segment of feeder, a transformer, a shunt capacitor, or other components between two buses. With the given voltage magnitude and phase angle at the root and known system load information, the power flow algorithm needs to determine the voltages at all other buses and currents in each branch. The forward/backward substitution algorithm employs an iterative method to update bus voltages and branch currents [6, 8].

Ladder Network theory

The ladder network theory given in [18] is similar to the forward-backward substitution method. Though the basic principle of both the methods is the same, there are differences in the steps of implementation. In the ladder network theory, the optimal ordering of nodes is done first. In the backward substitution, the node voltages are assumed to be equal to some initial value in the first iteration. The currents in each branch are computed by Kirchhoff's Current Law (KCL). In addition to the branch currents, the node voltages are also computed by using Kirchhoff's Voltage Law (KVL). Thus, the value of the swing bus voltage is compared with its specified value. If the error is within the limit, then the load flow converges; otherwise the forward substitution is performed as explained in the case of forward/backward substitution method.

Ratio-Flow method

Ratio-Flow method, which is known with its faster convergence characteristics amongst various sweep methods [12], is based on forward-backward ladder equation for complex distribution system by using voltage ratio for convergence control. The method is similar to the ladder network theory. The main difference between these methods is that a ratio of the new sending end voltage is calculated and the bus voltages are adjusted as given in eq. (1) after the backward process to obtain new bus voltages.

$$V_{s\_s} = \frac{V_s^{new}}{V_s} \tag{1-a}$$

$$V_k^{Adjust} = \frac{V_k^{new}}{V_{s\_s}} \tag{1-b}$$

$$V_{k\_r} = \frac{V_k^{new}}{V_s^{new}} \tag{1-c}$$

For each lateral, the voltage-ratio V_{k_r} is used as the lateral convergence target rather than the node voltage itself during the above speed-up forward-backward processes. When the lateral reaches lateral local convergence, the lateral total load current is calculated and added to its sending end on the main feeder.

III. Implementation of Voltage Regulators into Forward/Backward Sweep-Based Methods

In distribution systems, voltages along the primary feeders are often controlled by voltage regulators. These regulators are generally auto-transformers with individual taps on their windings. Typically, the regulator is used to boost (increase) or buck (decrease) the voltage by a variable amount up to 10%. Three-phase voltage regulators can easily be incorporated into the forward/backward sweep-based methods by means of series impedance in each phase and an ideal transformer with taps on the secondary side. In the manual mode, the tap position is initially set and so the ratio of the ideal transformer is known. Thus during the forward and backward sweep turns ratio will be applied to the line section current calculation and the node voltage calculation wherever the regulator is encountered. In the automatic mode, the tap position is unknown prior to the power flow algorithm. The implementation of voltage regulators into the ladder network theory and ratio-flow method are given as follow and in flow chart in fig.1.

Implementation of Voltage Regulators into the Ladder Network Theory

1. Calculate each branch current and new node voltages starting from the end of feeder moving toward to the voltage regulator secondary bus.
2. Calculate the new secondary voltage (V_{sr}^{new}) of each phase of the regulator.
3. Calculate the ratio of the new secondary voltage of the regulator and adjust the V_k^{new} starting from V_{sr}^{new} moving toward to the end as follow;

$$V_{s\_r} = \frac{V_{sr}^{new}}{V_{sr}} \tag{2-a}$$

$$V_k^{Adjust} = \frac{V_k^{new}}{V_{s\_r}} \tag{2-b}$$

4. Calculate each branch current and new node voltages starting from the primary side of voltage regulator to the swing bus.
5. Calculate the voltage mismatch for the swing bus. If voltage mismatch is lower than the convergence tolerance, stop the algorithm. On the other hand, apply forward sweep, and adjust the tap position as follow;
6. Calculate the node voltages starting from the swing bus to the regulator primary bus using KVL.
7. Calculate the secondary voltage, V_{sr} , of each phase of the regulator using the given tap values, and check if the voltage is within the lower and upper limits of the regulated voltage setting:

$$\left|V_{sr}^{min}\right| \le \left|V_{sr}\right| \le \left|V_{sr}^{max}\right| \tag{3}$$

If V_{sr} is greater than the upper limit, set the V_{sr} to the limit, calculate the new tap position and round it up to the nearest lower tap position. If V_{sr} is less than the lower limit, set V_{sr} to the limit, calculate the new tap position and round it up to the nearest upper tap position. Check if the obtained tap position exceeds the maximum boost or buck limits. If it does, set the tap at the corresponding limit.

8. Re-calculate V_{sr} using the new tap value and voltage ratio (a_t) as given in eq.(4), and then continue to the forward sweep.

$$a_t = V_{sr} + t_k * V_k \tag{4.a}$$

$$V_{sr} = a_t * V_{pr} \tag{4.b}$$

Where t_k and V_k show regulator tap position and each tap voltage level, respectively.

Implementation of Voltage Regulators into the Ratio-Flow Method

The same approach, given in section 3.1, is used for the implementation of automatic voltage regulator into the Ratio-Flow method as follow and it is also given in fig.2.

1. Calculate the each branch current and node voltages starting from far ends and moving toward to the voltage regulator.
2. Calculate the new secondary voltage (V_{sr}^{new}) of each phase of the regulator.
3. Calculate the ratio of the new secondary voltage of the regulator and adjust the V_k^{new} starting from V_{sr}^{new} moving toward to the end by using eq. (2).
4. Calculate each branch current and new node voltages starting from the primary side of voltage regulator to the swing bus.
5. Calculate the ratio of the new sending end voltage and adjust the V_k^{new} starting from swing bus to the regulator primary bus using eq. (1)
6. Calculate loads current profile and perform the forward process starting from swing bus moving toward to the primary voltage of regulator.
7. Calculate the secondary voltages of voltage regulator V_{sr}, and adjust the tap position as given in Section 3.1 in forward process.
8. Re-calculate the secondary bus voltages of voltage regulator V_{sr} using eq. (4) and continue the forward sweep.

It is noted that if the regulator secondary bus has a setting voltage value, in this case there is not need to adjusting of the tap position. Thus, the required tap position can be calculated using eq. (5) as follow.

$$a_t = \frac{V_{sr}^{set}}{V_{pr}} \tag{5.a}$$

$$t_k = \frac{a_t - V_{sr}^{set}}{V_k} \tag{5.b}$$

IV. Test Cases

To verify the modelling of voltage regulators for the sweep based algorithms, two test systems (IEEE 13-bus and 34-bus systems) are used and the results are compared. For the test systems all loads are considered being star connected and mutual capacitance between phases are neglected. Sweep based algorithms are applied to these systems for comparison purpose and all algorithms are coded in Matlab. In the load flow solution, the AVR's tap position is adjusted to keep its secondary bus voltages at the level which is given in load flow solution of the test systems in [20]. Table 1 shows the power flow solutions obtained by using forward/backward substation algorithm [6], Ratio-Flow method [12] and Ladder Network Theory [18] for IEEE 34-bus system. From Table 1 it is seen that the results are in close agreement. It is also observed from the result of IEEE 13-bus system, they are not presented here due to the page limitation. From the load flow solution of the test systems it is concluded that the proposed approach for the incorporating of the voltage regulator into the sweep algorithms is robust and simple. In addition, iteration number and memory requirements of each algorithm are less affected when the AVRs are applied as can be seen from Table 2. Although the number of iterations for the algorithm may arise seven these systems without AVR's, it takes maximum 8 iterations when the AVR's are included to the load flow analysis.

V. Conclusion

In this study, distribution system voltage regulators are incorporated into the sweep-based power flow algorithm. The automatic voltage regulator model which is previously applied to forward stage of the sweep-based algorithm is extended for the Ladder Network Theory and Ratio-Flow method which has forward and backward voltage calculation. From the test results, it can be said that the proposed model is valid and reliable, and the performance of the algorithms is not significantly affected from the inclusion of regulator modelling.

Acknowledgements

This work is supported by the Research Fund of TUBITAK under the project number of 106E132, 2006.

References

1. IEEE Tutorial Course on Power Distribution Planning, IEEE Power Engineering Society, 92 EHO 381-6 PWR.
2. Shoults R.R, Chen M.S., and Schwobel L., Simplified feeder modeling for load flow calculations, IEEE Transactions Power Systems, vol.2, pp.168-174, 1987.
3. T.-H. Chen, M.-S. Chen, K.-J. Hwang, P. Kotas, and E. A. Chebli, Distribution system power flow analysis – A rigid approach, IEEE Trans. on Power Delivery, vol. 6, pp. 1146–1152, July 1991.
4. D. Rajicic, R. Ackovski, and R. Taleski, Voltage correction power flow, IEEE Trans. on Power Delivery, vol. 9, pp. 1056–1062, Apr. 1994.
5. R. D. Zimmerman and H.-D. Chiang, Fast decoupled power flow for unbalanced radial distribution systems, IEEE Trans. on Power Systems, vol. 10, pp. 2045–2052, Nov. 1995.
6. C. S. Cheng and D. Shirmohammadi, A three-phase power flow method for real-time distribution system analysis, IEEE Trans. Power Systems, vol. 10, pp. 671–679, May 1995.
7. F. Zhang and C. S. Cheng, A modified Newton method for radial distribution system power flow analysis, IEEE Trans. on Power Systems, vol. 12, pp. 389–397, 1997.
8. D. Thukaram, H. M. W. Banda, and J. Jerome, A robust three-phase power flow algorithm for radial distribution systems, Electric Power Systems Research, vol.50, pp.227-236, June 1999.
9. V. M. Da Costa, N. Martins, and J. L. Pereira, Development in the Newton Raphson power flow formulation based on current injections, IEEE

Transactions on Power Systems, vol. 14 (4), pp.1320-1326, November 1999.

10. Whei-Min Lin, Jen-Hao Teng, Three-phase distribution network fast-decoupled power flow solutions, Electrical Power and Energy Systems, vol.22, pp.375-380, 2000.
11. J. H. Teng, A network-topology based three-phase load flow for distribution systems, Proceedings of National Science Council ROC (A), vol.24 (4), pp.259-264, 2000.
12. J. Liu, M.M.A. Salama and R.R. Mansour, An efficient power flow algorithm for distribution systems with polynomial load, International Journal of Electrical Engineering Education, vol. 39 (4), pp.372-386, 2002.
13. J.H. Teng, A modified Gauss-Seidel algorithm of three-phase power flow analysis in distribution networks, Electrical Power and Energy Systems, vol.24, pp.97-102, 2002.
14. J. C. M. Vieria, W. Freitas and A. Morelato, Phase – decoupled method for three-phase power-flow analysis of unbalanced distribution systems, IEE Proc.-Gener. Transm. Distrib., vol.151(5), pp. 568-574, Sep. 2004.
15. M. Abdel-Akher, K. Mohamed Nor. and A. H. Abdul Rashid, Improved three-phase power-flow methods using sequence components, IEEE Transactions on Power Systems, vol. 20 (3), pp.1389-1397, August 2005.
16. X. P. Zhang, W. J. Chu, H. Chen, Decoupled asymmetrical three-phase load flow study by parallel processing, IEE Proc.-Gener. Transm. Distrib., vol.143 (1), pp.61-65, January 1996.
17. W. M. Lin, Y.-S. Su, H.-C. Chin, and J.-H. Teng, Three-phase unbalanced distribution power flow solutions with minimum data preparation, IEEE Trans. on Power Systems, vol. 14, pp. 1178–1183, Aug. 1999.
18. W. H. Kersting, Distribution system modeling and analysis. Boca Raton, FL: CRC Press, 2002.
19. G. T. Heydt, Electric Power Quality, Second edition Stars in Circle Publications, West LaFayette, IN, 1991.
20. Radial Test Feeders-IEEE Distribution System Analysis Subcommittee, available at: www.ewh.ieee.org/soc/pes/dsacom/testfeeders.html

Table 1. Power flow solution of the IEEE 34-bus test system

Bus No	Forward/Backward Sub [6].			Ratio-Flow [12]			Ladder Network Theory [18]		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
800	1.0500	1.0500	1.0500	1.0500	1.0500	1.0500	1.0500	1.0500	1.0500
802	1.0482	1.0486	1.0483	1.0482	1.0486	1.0483	1.0482	1.0486	1.0483
806	1.0470	1.0477	1.0471	1.0470	1.0477	1.0471	1.0470	1.0477	1.0471
808	1.0238	1.0317	1.0264	1.0238	1.0317	1.0264	1.0238	1.0317	1.0264
812	0.9968	1.0140	1.0017	0.9968	1.0140	1.0017	0.9968	1.0140	1.0017
814	0.9753	0.9997	0.9820	0.9753	0.9997	0.9820	0.9753	0.9997	0.9820
850	1.0176	1.0255	1.0203	1.0176	1.0255	1.0203	1.0176	1.0255	1.0203
816	1.0173	1.0253	1.0201	1.0173	1.0253	1.0200	1.0173	1.0253	1.0201
824	1.0106	1.0164	1.0105	1.0106	1.0164	1.0105	1.0106	1.0164	1.0105
828	1.0100	1.0158	1.0097	1.0100	1.0158	1.0097	1.0100	1.0158	1.0097
830	0.9966	1.0001	0.9903	0.9966	1.0001	0.9903	0.9966	1.0001	0.9903
854	0.9963	0.9997	0.9898	0.9963	0.9997	0.9898	0.9963	0.9997	0.9898
852	0.9731	0.9718	0.9565	0.9731	0.9718	0.9565	0.9731	0.9718	0.9565
832	1.0359	1.0345	1.0360	1.0359	1.0345	1.0360	1.0359	1.0345	1.0360
858	1.0342	1.0321	1.0330	1.0342	1.0321	1.0330	1.0342	1.0321	1.0330
834	1.0323	1.0293	1.0296	1.0323	1.0293	1.0295	1.0323	1.0293	1.0296
860	1.0321	1.0288	1.0287	1.0321	1.0288	1.0287	1.0321	1.0288	1.0287
836	1.0317	1.0285	1.0285	1.0317	1.0285	1.0285	1.0317	1.0285	1.0285
862	1.0317	1.0284	1.0285	1.0317	1.0284	1.0285	1.0317	1.0284	1.0285
838	-	1.0281	-	-	1.0281	-	-	1.0281	-
810	-	1.0314	-	-	1.0314	-	-	1.0314	-
818	1.0164	-	-	1.0164	-	-	1.0164	-	-
820	0.9905	-	-	0.9904	-	-	0.9905	-	-
822	0.9844	-	-	0.9842	-	-	0.9844	-	-
826	-	1.0160	-	-	1.0160	-	-	1.0160	-
856	-	0.9995	-	-	0.9995	-	-	0.9995	-
888	1.0008	0.9992	1.0007	1.0008	0.9992	1.0007	1.0008	0.9992	1.0007
890	0.9187	0.9250	0.9185	0.9187	0.9250	0.9185	0.9187	0.9250	0.9185
864	1.0342	-	-	1.0342	-	-	1.0342	-	-
842	1.0323	1.0292	1.0295	1.0323	1.0292	1.0295	1.0323	1.0292	1.0295
844	1.0321	1.0289	1.0293	1.0320	1.0289	1.0293	1.0321	1.0289	1.0293
846	1.0323	1.0287	1.0295	1.0323	1.0287	1.0294	1.0323	1.0287	1.0295
848	1.0323	1.0287	1.0295	1.0323	1.0287	1.0295	1.0323	1.0287	1.0295
840	1.0317	1.0284	1.0285	1.0317	1.0284	1.0285	1.0317	1.0284	1.0285

Table 2. Iteration number of algorithms for test systems

Methods	Number of iteration	
	IEEE 13-bus	IEEE 34-bus
Forward/Backward Sub. [6]	6	8
Ratio-Flow [12]	7	7
Ladder Network Theory [18]	6	7

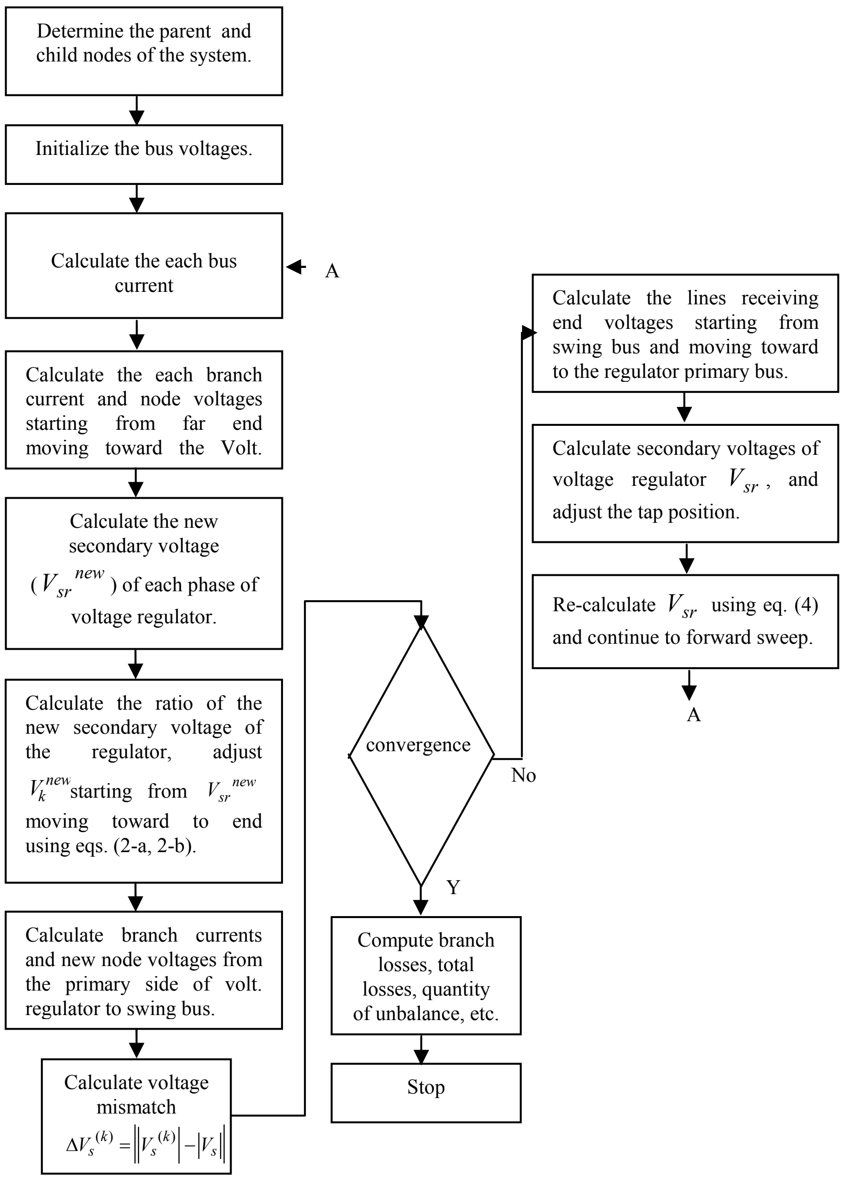

Figure 1. Flow chart for Ladder Network Theory with AVR.

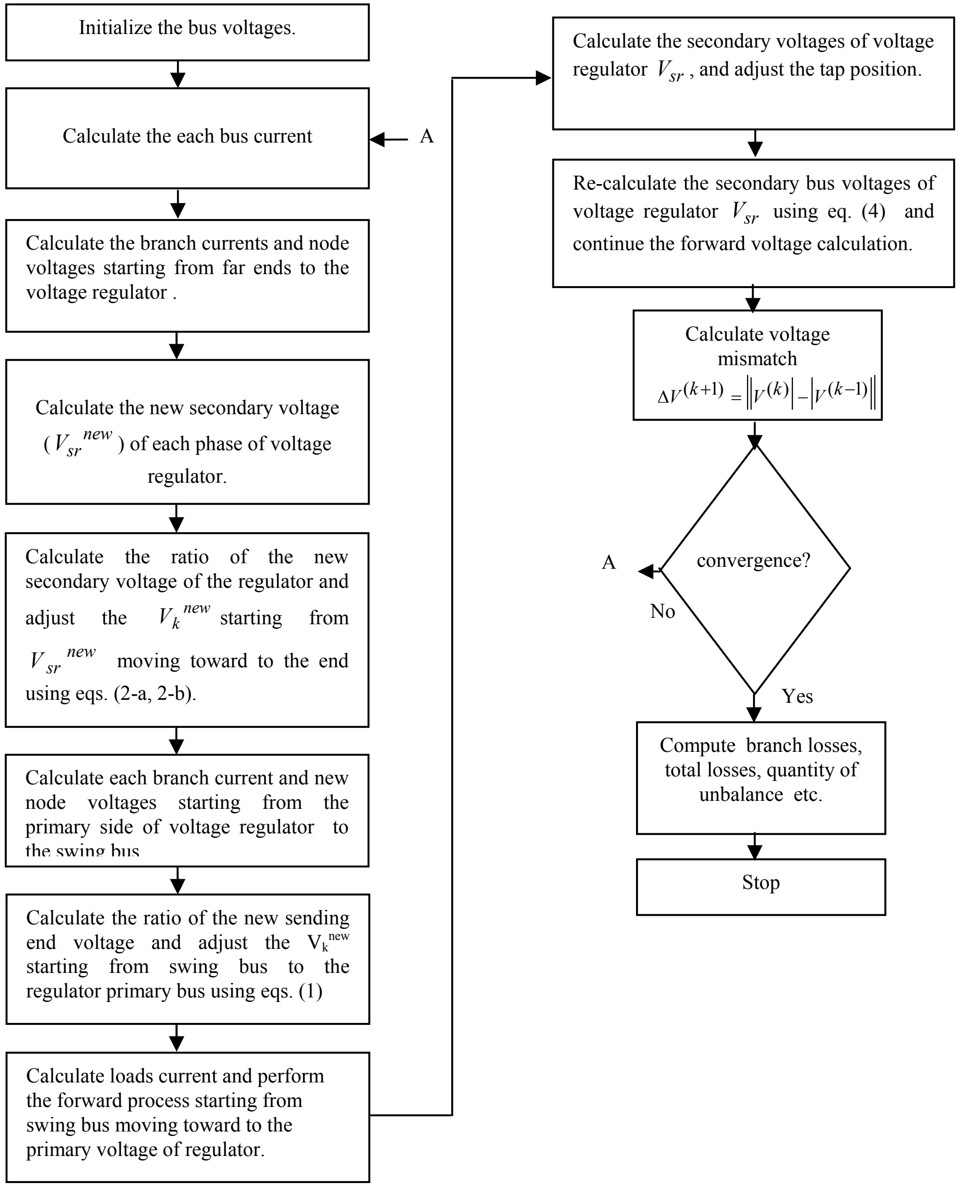

Figure 2. Flow Chart for Ratio-Flow method with AVR