Inclusion of slack bus in Newton Raphson load flow study

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Introduction

The buses of power system are of 3 types- PV, PQ and Slack where slack is also referred to as infinite bus due to its infinite generating capacity. It carries all the losses of the network. It is impossible for application of conventional power flow solution techniques in microgrids to use only one slack bus because generating units are compared to their sizes. Thus, it is impossible to find a bus of infinite capacity. Thus, slack bus should be treated as a normal PV bus and be included in the iterative process. Distribution systems have special characteristics which calls for the use of distributed slack bus more than a single slack bus. We use the loss equation to modify the Jacobian in Newton-Raphson method which would be used to solve the load flow for two conditions- when the slack is carrying all the losses and when the losses are distributed.

Mathematical Formulation

For a given load system, all loads except slack are known beforehand. In the start, the losses are assumed to be zero and the generators are sufficient to supply to the loads. After each iteration the total power is calculated and is included with the scheduled power of the slack bus.

The apparent power injected at bus i is given by

$$S_i = P_i + jQ_i = V_i I_i^* = V_i \sum_{k=1}^{n} V_k^* Y_{bus_{ik}}^*$$

Where the real power is given by Pi and the reactive power is given by Qi.

Since the slack bus will bear the total losses of the system, we will add the loss calculated after each iteration is added with the original scheduled power considered at the beginning of the iteration. The original scheduled real power at slack bus can be equated with the injected power obtained from equation minus the losses calculated after each iteration.

P1=P1-loss

By combining the above equation and the real power equation we get

$$P_1' = \mathrm{Re}\left[V_1^* \sum_{ik=1}^{n} V_k Y_{bus_{ik}} \right] - loss$$

The total loss is now expressed as,

$$loss = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} \left| (V_i - V_k)^2 Y_{bus_{ik}}^2 \operatorname{Re}\left[\frac{-1}{Y_{bus_{ik}}}\right] \right|$$
$$= \sum_{i=1}^{n-1} \sum_{k=j+1}^{n} |(V_i - V_k)^2 C_{ik}|$$

The elements of the Jacobian corresponding to delta(P) is given by,

$$\frac{\partial P_1}{\partial \delta_1} = \frac{\partial}{\partial \delta_1} \left\{ \operatorname{Re}\left[V_1^* \sum_{k=1}^{n} V_k Y_{bus_{ik}} \right] \right\} - \frac{\partial loss}{\partial \delta_1}$$
$$\frac{\partial P_1}{\partial |V|_1} = \frac{\partial}{\partial |V|_1} \left\{ \operatorname{Re}\left[V_1^* \sum_{k=1}^{n} V_k Y_{bus_{ik}} \right] \right\} - \frac{\partial loss}{\partial |V|_1}$$
$$< \text{Conventional term} > \quad < \text{new term} >$$

The above terms are obtained by differentiating the total loss with $\delta 1$ and |V1| respectively. Now, resolving the above equations we get,

$$\frac{\partial loss}{\partial \delta_1} = 2 \sum_{\substack{k=1 \\ k \neq i}}^{n} C_{1k}(V_1 - V_k) j V_1$$
$$\frac{\partial loss}{\partial |V|_1} = 2 \sum_{\substack{k=1 \\ k \neq i}}^{n} C_{1k}(V_1 - V_k) e^{j\delta_1}$$

Therefore, the elements of the Jacobian are updated by the above two equations.

This iteration process considers all the buses hence the angles of all the buses are subject to change. Thus, all the bus voltages are rotated in the opposite direction with the angle.

Test

For the validation of the new method, a 6-bus system is selected. The figure for the single line diagram of the system is shown below. The method developed has also been applied to a 30-bus and 57-bus IEEE test systems. Table 1 represents the salient information on the three systems.

6-bus test system

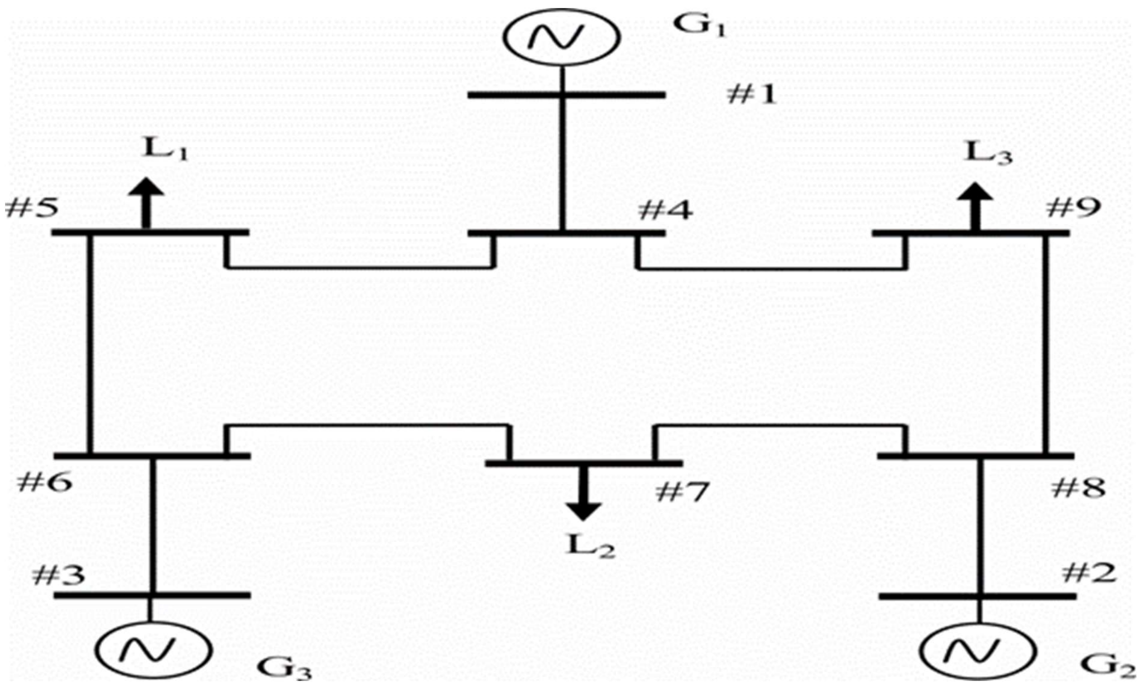

Table – I Data on the systems studied

Items	6-bus	30-bus	57-bus
Scheduled Gen. at Slack bus (at the beginning of iteration), MW	100	23.53	450.8
Scheduled generation at other gen. buses, MW	110	165.67	800.0
Total load, MW	210	189.3	1250.8
No. of genenrator bus	3	6	4
Total no. of bus	6	30	57

Results

An open-source MATLAB program, MATPOWER, for load flow studies has been modified to implement the method developed and described above. Conventional Newton-Raphson method for load flow solutions has been implemented by the original program.

The validity of the formulation is established by applying the proposed method and the conventional N-R method for the load flow solutions of the test systems mentioned earlier and comparing results. While applying the proposed formulation two different case has been considered, (i) losses included in the slack bus generation only and (ii) losses distributed among all the generator buses.

A. Validation of the Developed Method

The slack bus is added to the Jacobian in the updated algorithm, and the program is run for the 6-bus system. After three iterations, it converged. After that, the 6-bus system with the same slack bus is run using the standard N-R software. The traditional approach likewise required three iterations to reach convergence. Following convergence, 107.88 MW is discovered to be the slack bus power. The losses are discovered to be the same for both strategies. Additionally, the voltage magnitudes and angles determined using the two techniques were identical. To compare the injected power to the slack bus's scheduled power, the losses were estimated for each iteration of the updated program and deducted from the injected power. The losses obtained in different iterations are tabulated in Table II.

Table- II Convergence of loss for 6 bus systems

Iteration count	Losses, MW	Net Power at bus 1, MW
1	7.55	107.55
2	7.87	107.87
3	7.88	107.88

Similar studies have been carried out for the 30-bus and the 57-bus IEEE systems. It was also discovered that the standard and modified approaches used the same number of iterations in both situations. It has been found that for all systems, the convergence of real and reactive powers occurs earlier when loss estimates are determined during an iterative procedure. It suggests that it is accurate to include loss and its impact on Jacobian.

B. Loss Distributed Over All Generator Buses

Since the generating capacities in a microgrid are equal, it might not be viable to place the full burden of losses on a single generator. The created approach was used in a 57-bus system, and the entire losses were divided among the four generating buses in accordance with their capacity. Table III displays the outcome. The table contrasts the losses for the two scenarios, namely the losses dispersed over all generator buses and the losses solely included in the slack bus generation. The outcome shows that spreading the loss across buses of various generations reduces it. This outcome is more accurate. This type of study is now possible with the developed method.

Table-III comparison between non-distributed and distributed systems

Gen. Bus	Losses applied to slack bus		Losses distributed among gen. buses	
	Losses, MW	Gen. power, MW	Loss, MW	Gen. power, MW
1	27.86	478.36	9.64	459.64
3	0.0	40.0	0.86	40.86
8	0.0	450.0	9.63	459.63
12	0.0	310.0	6.63	316.63
Total	27.86	1278.36	26.76	1277.26

Conclusion

A technique for incorporating the slack bus into the Newton-Raphson method's iterative process has been presented. It is based on inclusion of line losses at every iteration. The expressions of the change of loss with voltage magnitudes and their angles have been applied in the study together with an analysis of the mathematical formulation of this influence.

The formulation's validity has been tested in three test systems. The consistency of the development was demonstrated by the outcomes of the new method and the conventional one agreeing. The new method is also used in a scenario where losses are dispersed throughout several generator buses. The simplicity of the new method has created a new channel for investigating many studies that are not feasible using the conventional method.

References

https://ieeexplore.ieee.org/document/7026900