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Distributed AC power flow method for AC and AC-DC hybrid autonomous microgrids with droop control

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Abstract

Power flow methods are one of the powerful tools used in the analysis of stable and reliable operation of the electric power systems. Conventional power flow methods make use of slack bus, PV and PQ bus, low R/X ratio in the formulation of the power flow. These assumptions while considering autonomous microgrids (MGs), with small sources and low voltage connection lines, are not suitable. Present MGs incorporate AC and DC sources and loads along with storage and power electronic conversion devices. In light of these facts, a distributed power flow method (DPFM) for autonomous microgrids is presented here that solves the power flow problem node-wise, minimizing losses and does not consider slack, PV or PQ buses. In order to have proper control over the load sharing among the sources, a modified droop control is used. The proposed DPFM can be used for AC low voltage (LV) autonomous microgrid systems with added advantages of remedying the dependency on voltage level and R/X ratio in the formulation itself. DPFM is applied on a 10 bus, low voltage, microgrid system giving a better voltage profile..

Keywords: Microgrid (MG), Distributed Energy Resources (DER), Particle Swarm Optimization (OPF), Time varying inertia weight (TVIW), Distributed power flow method (DPFM)

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1. Introduction

Small scale fossil fuel based generation systems, renewable energy based sources, electric vehicles, battery and other types of storage systems etc. work alongside high inertial conventional power generation systems, when the renewable based MGs work in the grid connected mode. In such systems stability of the MGs are not a troublesome issue considering the presence of the heavy generator cluster powered grid. This is not the situation when the MG is working in the autonomous or grid disconnected mode, same as in cases when the grid is disconnected due to fault or repair upstream. For the extraction of maximum benefits off the MGs and cope with the challenges arousing during the autonomous operation of the same, proper survey and analysis of different system components is a necessity (Kamh et al., 2011). Many a tool exists for the management of traditional power system that are well established, but is not suitable for MGs, that are usually medium or low voltage systems (Nikkhajoei et al., 2007).

A basic yet powerful tool put to use especially in analysis of autonomous MGs is performing power flow analysis (Kamh et al., 2010). The power flow methods used for traditional power system are designed for systems with very low R/X ratio and where there are sources so powerful that the concept of slack bus or buses based voltage and frequency regulation, PV and PQ bus are suitable assumptions. But in case of renewable based MGs, where small and intermittent sources are connected to low/medium voltage connection lines with considerable R/X ratio, where the rise in power is managed by the reduction in frequency and voltage, the above mentioned assumptions does not hold well (Elrayyah et al., 2014). The conventional power flow methods fail to converge or guarantee solution in systems with high R/X ratio and radial in nature (Dall'Anese et al., 2013).

Modern distribution networks, to be precise, modern active distribution networks, differ from the conventional distribution systems because of the presence of DGs. Sedghi et al. (2012) suggests that unlike conventional radial distribution systems, the modern networks includes several loops. Hence the distribution power flow models to be developed were supposed to include both mesh and DG modeling (Sedghi et al., 2012). Hence the creation of low voltage compatible power flow methods devoid the above mentioned dependencies is a necessity.

Different distribution power flow methods have been suggested in literatures. Newton-Raphson based power flow methods, namely Newton Downhill method (NDM) and Current Injection method (CIM) are described in literatures (Singh et al., 2008; Araujo et al., 2006; Costa et al., 2001). NDM method though independent of the initial point of computation and better convergence rate owing to the use of a downhill factor, a varying coefficient to narrow down to the solution, it cannot cope with the singularity of Jacobian matrix (Singh et al., 2008). CIM has better success when used with systems of high R/X ration when compared to NDM, but have convergence issues if number of PV buses is more (Sedghi et al., 2012; Kamel et al., 2010). In (Elrayyah et al., 2014), another NR based method is formulated for LV systems. Backward Forward Sweep (BFS) method has been a great success considering the fast convergence, simple concept and suitability to radial systems. But the deficiency of the method lies in the fact that it cannot be used for meshed systems. Optimization based methods include GA based and PSO based power flow methods. They also have the added advantage that they do not create jacobian matrices and are devoid of R/X ratio issues (Achejee et al., 2009).

This paper endeavors to create a power flow method, applicable to LV autonomous AC microgrid systems, that can incorporate various R/X ratios and that gives the buses/nodes the flexibility to have variable power generation and voltage. DPFM proposed here solves the power flow method by considering the nodal equations. The power flow problem is approached as a simple optimization problem minimizing losses and uses PSO-TVIW for solving the problem. A separate power flow method is not used for solving. DPFM is formulated such that R/X ratio of any value can be considered. The active and reactive power dependencies on voltage and frequency are not taken as decoupled and a modified droop equation has been used. A 10 bus, 120 V, three generator and four load, meshed system described in (Elrayyah et al., 2014) is used for testing the proposed method. The result showed better voltage profile and lower deviation in the voltage from the nominal value.

Section III describes the problem formulation with the different power flow equations used. Section IV describes the solving technique followed by Section V describing the result and comparison with previous literature, (Elrayyah et al., 2014).

2. Problem Formulation

The DPFM method proposed approaches the power flow problem and solves it in a nodal fashion. As described before, since most generators are quite small and unpredictable, they are not able to regulate the voltage and frequency during a contingency and hence cannot be classified as PV or PQ bus. The different AC buses/nodes in the power system can be classified into three as mentioned in (Elrayyah et al., 2014) as below

- Gbus – Generator bus
- Lbus – Load bus
- Cbus – Connector bus

Gbus is the set of buses containing generators. They may house local loads too. They can also include battery stations or electric vehicle (EV) charging station while they are in the discharging mode. Lbus includes buses with loads and no power generation. Battery or EV stations in the charging mode come under this category. Cbus houses neither generation nor load. Nodal power balance equation for Lbus is given in (1). At the point of equilibrium when the loads are met by the available sources, the incoming real and reactive power at the load bus shall be same as the load requirement. Equation (1) is the mathematical realization of this concept.

$$[(P]_{Li} + jQ_{Li}) + U_{Li}\angle\delta_{(Li)}\ [(\Sigma_{K} \equiv [\ [((U]_{Li}\angle\delta_{Li} - U_{K}\angle\delta_{K}]\ ) * Y_{LiK}\angle\theta_{LiK})]^{\dagger} * = 0 \tag{1}$$

Similarly for the Cbus, the absence of a power generation or consumption component implies that the incoming and outgoing power should be the same. The nodal power balance for the Cbus is mathematically represented in (2). This is valid since the system is LV system and the shunt charging elements are negligible and hence not considered. Even when the shunt elements are to be considered, then right hand side of Equation (2), becomes non-zero as it gets replaced by the power consumed by the shunt element, which can be calculated from the bus voltage.

$$(U_{Ci}\angle\delta_{Ci}).\sum_{K}\left((U_{Ci}\angle\delta_{Ci} - U_{K}\angle\delta_{K}).\,Y_{CiK}\angle\theta_{CiK}\right)^{*} = 0 \tag{2}$$

At the Gbus, the power generated by the generator should be equal to the difference between the power injected from the bus and the power consumed at the bus, which is represented in (3). Since the amount of active and reactive power generated is unknown prior to the execution of power flow, this realization is not possible at the initial stages.

$$S_{Gi} = S_{LGi} + S_{inj,Gi} \tag{3}$$

The decoupling of active and reactive power from voltage and frequency is primarily supported by the assumption that the R/X ratio is very small and hence the resistive components of the system power lines be neglected. This assumption however is not suitable for a low voltage system, where the R/X ratio is not negligible. Hence in this paper, a modified droop equation as given in (4) is considered, which does not decouple P or Q from U or δ.

$$\begin{aligned} \delta &= \delta ref - K1^{pf}(P) - K3^{qf}(Q) \\ U &= Uref - K2^{pv}(P) - K4^{qv}(Q) \end{aligned} \tag{4}$$

3. DPFM Solution Method

The nodal power flow equations provided in the previous section are satisfied only after the power flow converges. In other words, if the voltage magnitude, voltage angle and current values obtained from the power flow after convergence is known, then only the power balance equations from (1) to (3) will be satisfied. If a random set of values are assigned to the variables present in the equations mentioned above, then these equations will result in a non-zero value. In light of this fact, optimization based power flow method, modified from the one described in (Acherjee et al., 2009), is used for solving the power flow problem.

This method involves solving the power flow problem as a simple optimization problem. A power flow problem requires certain conditions to be satisfied like, net power generation should be same as the sum of loads and losses, the generators should not be loaded above or below their maximum and minimum loading points, the line flows should be less than the line loading limit, etc. This set of equality and inequality constraints, common to any power system problem is categorized as system constraints and are given in equation (3) and the equations (5)-(7).

$$\sum_i S_{Gi} - \left(\sum_i S_{Li} + Losses \right) = Err_G \tag{5}$$

$$V_{i,min} \leq V_i \leq V_{i,max}$$

$$P_{ij} \leq P_{ij,max} \tag{6}$$

$$P_{Gi,min} \leq P_{Gi} \leq P_{Gi,max} \tag{7}$$

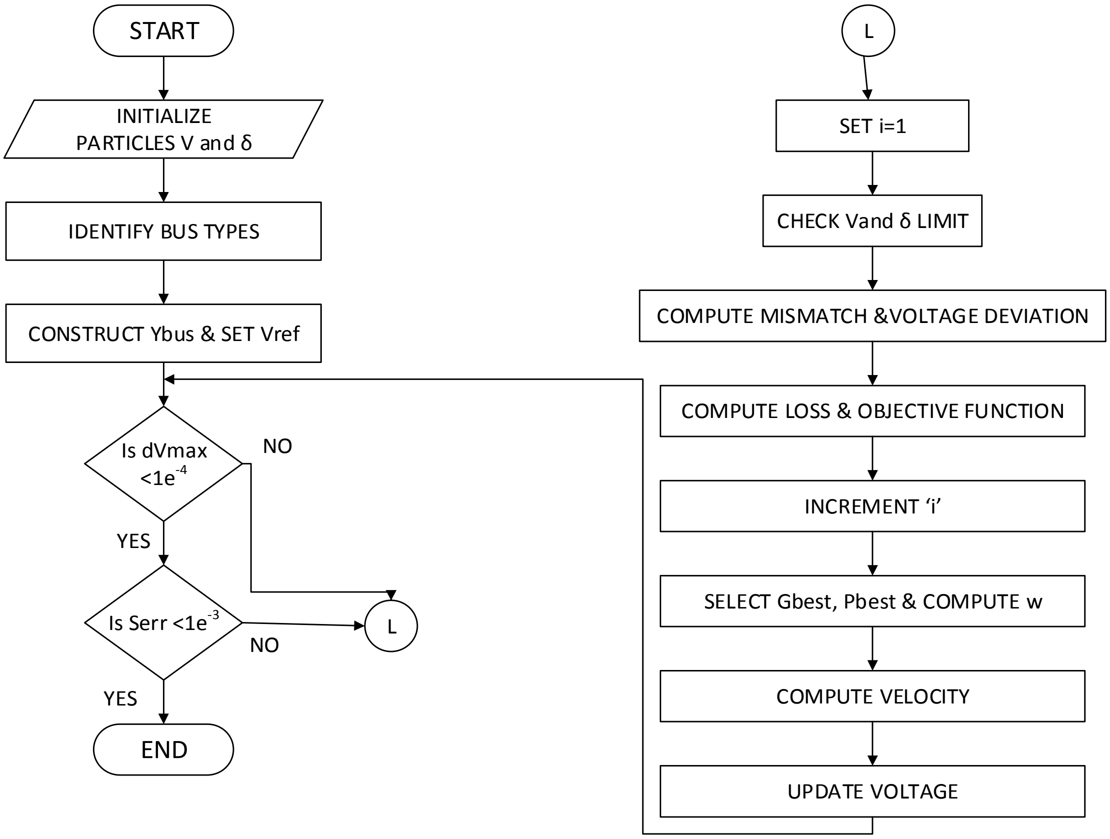

Figure 1. Flow chart for DPFM

In addition to these, for the power flow to converge, the nodal power balance equations mentioned in the previous section should also be satisfied or the errors in those equations should be in an acceptable limit. These power balance equations are incorporated as pseudo-equality constraints and named power flow constraints. These constraints are given in the equation set (8).

$$P_{Li} + jQ_{Li} - S_{Li,calc} = ErrL_i$$
$$(U_{Ci}\angle\delta_{Ci}).\sum_{K}\left((U_{Ci}\angle\delta_{Ci} - U_K\angle\delta_K).Y_{CiK}\angle\theta_{CiK}\right)^* = ErrC_i \tag{8}$$

The objective function is formulated as a sum of the mismatch terms, weighted so that towards the point of convergence all the terms come in the same range. The minimization of this term objective functions shall lead to point of convergence of the power flow problem. This objective function is augmented with a weighted power loss term such that the final power flow result shall not only give a power flow solution but an optimal one. The objective function is given in (9).

$$Min\ \{k_1.|Loss| + k_2.|ErrG| + k_3.|ErrC_i| + k_5.|ErrL_i|\} \tag{9}$$

In order to solve this optimization problem, PSO-TVIW described in (10) and (11), is used. The flowchart showing the working DPFM is given in Fig. 1.

$$V_i(t+1) = w^k.V_i(t) + c_1.rand_1(P_{ibest} - X_i(t)) + c_2.rand_2(G_{ibest} - X_i(t))$$
$$X_i(t+1) = X_i(t) + V_i(t+1) \tag{10}$$
$$w^k = w_{max} - (w_{max} - w_{min})\frac{k}{I_{max}} \tag{11}$$

The values for W_{max} and W_{min} 0.9 and 0.4 respectively. DPFM continues to execute until the errors in the power flow constraints are within affordable range and the system constraints are also satisfied. The tolerance in nodal power mismatch used in 0.001.

4. Results and Discussion

A 10 bus LV system described in (Elrayyah et al, 2014). Comprising of three generators, four loads and three connector buses, as shown in Fig. 2, the considered system is 120V, 50Hz. The network lines in the system are a combination of high and low R/X ratios. Instead of constant power load models, the system makes use of constant impedance load model. This helps in realizing a more realistic load system by incorporating the effects of voltage change on the load. Hence the load value varies in every iteration as the voltage is updated. Details of the load model used in the problem are given in Table 1.

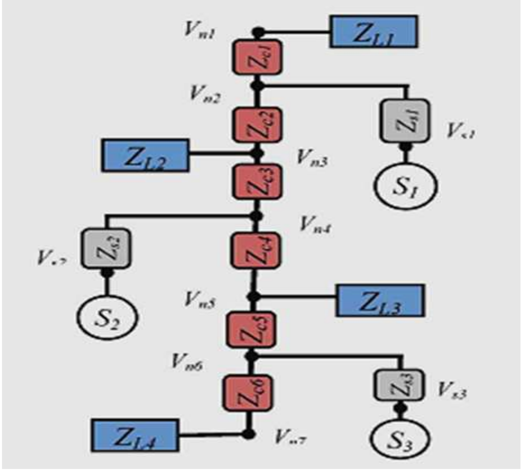

Figure 2. 10 bus LV system (Elrayyah et al., 2014)

As mentioned in the previous section, the (complex voltage) voltage magnitude and angle are selected as the particles for the PSO-TVIW. After evaluating the objective function, the particle set giving the minimum value of the objective function is taken as the global best particle and the Pbest or particle best value is also updated when the objective function value obtained is lower for the particle set. The process is continued till the nodal mismatch values are negligibly small.

The proposed power flow method was applied on the 10 bus system with the load values as given in Table 1. With the PSO applied on particle sets of 30 and the convergence criteria set as the maximum mismatch value to be lesser than 0.001, DPFM converges in 0.2983 seconds. The voltage deviation has been minimized to +/-2 V from the nominal value of 120 V and a better voltage profile is obtained except at bus no.4. Table 2 shows the bus voltage comparison. Table 3 shows the full result of DPFM. The better results attributes to the use of droop control helping the sources share the load in an optimal manner and also the fact that the system is completely uncoupled. A more accurate formulation has been adopted with lesser number of assumptions. This method can also be used an optimal sizing tool for a low voltage microgrid system. Also the optimal power flow formulation helps in the incorporation and modification of the optimizing objectives.

Table 1. Load data (Elrayyah et al, 2014)

Load bus no.	Load R lower (Ω)	Load X lower (Ω)
4	8	15
5	14	20
6	15	24
7	9	10

Table 2. Bus voltage comparison

Bus no.	Voltage (V) (Elrayyah, 2014)	Voltage (V) DPFM
1	119.93	121.9922
2	119.87	122
3	119.81	121.6331
4	118.37	118.1436
5	118.44	119.2507
6	117.87	121.8766
7	117.87	121.7116
8	117.64	121.7047
9	117.49	120.5869
10	117.12	118.214

Table 3. DPFM results for 10 bus system

Bus no.	Bus Voltage (V)	δ (radians)	Active power generation (Watts)	Active power demand (Watts)	Reactive power generation (VARs)	Reactive power demand (VARs)
1	121.9922	0	998.9	0	442.2	0
2	122	-0.012	601.7	0	961.1	0
3	121.6331	-0.016	237	0	583	0
4	118.1436	-0.0164	0	282.4	0	846.8
5	119.2507	-0.0185	0	331.7	0	473.8
6	121.8766	-0.0185	0	260.7	0	417.2
7	121.7116	-0.0186	0	496.9	0	207
8	121.7047	-0.0186	0	0	0	0
9	120.5869	-0.0186	0	0	0	0
10	118.214	-0.018	0	0	0	0

5. Conclusions

A distributed power flow method applicable to LV systems is proposed. The method is formulated such that it can incorporate different values of R/X ratio and the droop control is also modified to accommodate the same. The system formulation also facilitates the methods to be applicable to AC autonomous microgrid systems. DPFM was applied on a 10 bus system, LV system that uses constant load models. Voltage profile of the system was found to be improved and a lower tolerance level could be achieved using the same method and in a short time.

Nomenclature

P_{Li}	Active power demand at Load bus ‘Li’
Q_{Li}	Reactive power demand at Load bus ‘Li’
U_{Li}	Bus voltage magnitude at Load bus ‘Li’
UC_i	Bus voltage magnitude at Connector bus ‘Ci’
U_{ref}	Reference bus voltage
U_{Lac}	AC voltage magnitude at the load bus
δ_{Li}	Bus voltage angle at Load bus ‘Li’
δ_{Ci}	Bus voltage angle at Connector bus ‘Ci’
δ_{ref}	Reference of bus voltage angle

$K1^{pf}$	Frequency droop coefficient for active power
$K3^{qf}$	Frequency droop coefficient for reactive power
$K2^{pv}$	Voltage droop coefficient for active power
$K4^{qv}$	Voltage droop coefficient for reactive power
$S_{Li,calc}$	Calculated incoming power to load bus
$ErrL_i$	Mismatch in calculated and specified power at load bus
$ErrC_i$	Mismatch in incoming and outgoing power at load bus
$V_i(t)$	PSO particle velocity at iteration‘t’
w^t	Inertia weight at iteration ‘t’
c_1, c_2	PSO acceleration constants
$rand_1$	PSO random constant
$rand_2$	PSO random constant
G_{ibest}	PSO global best
P_{ibest}	PSO particle/individual best
$X_i(t)$	Position of particle

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