LOAD FLOW CALCULATIONS IN AC/DC DISTRIBUTION NETWORK INCLUDING WEAKLY MESH, DISTRIBUTED GENERATION AND ENERGY STORAGE UNITS

Saeed MOUSAVIZADEH
Tarbiat Modares University – Iran
Saeed.mousavizadeh@modares.ac.ir

Mahmoud Reza HAGHIFAM
Tarbiat Modares University – Iran
haghifam@modares.ac.ir

ABSTRACT

The technical and economical developments during last decades have established opportunity to create a new competitive distribution system based on modern power electronic technology. From technological point of view the LVDC system is a new concept in the field of electricity distribution. In general, two basic approaches have been reported for solving the AC-DC network power flow equations: sequential and unified methods.

Similar to AC distribution networks, due to the large number of PQ buses and high r/x ratio, methods such as Newton Raphson and FAST Decoupled cannot be used in these systems; introduced methods also cannot be used in AC/DC distribution networks. In this paper, load flow calculations are studied in AC/DC distribution networks including a weakly mesh, in the presence of distributed generation and energy storage units, taking into account different converter control strategies, by backward forward sweep and compensation-based algorithms.

INTRODUCTION

The demand for higher quality and reliability of power distribution system, role of distribution system in reducing losses and pollutions have increased utilization of power electronics devices in distribution systems. From technological point of view, the LVDC system is a new concept in the field of electricity distribution. An LVDC distribution system constructs of power electronic converters and DC link between the converters [1].

As in the case of an AC power system, operation of a power system with DC transmission lines requires a power flow analysis to compute bus voltages, bus angles, active power flow, and reactive power flow for specified generation and load conditions. With DC grids, an additional treatment is required for a hybrid AC-DC power flow [2]. In general, two basic approaches have been reported for solving the AC-DC power flow equations: sequential and unified methods. The main differences between the two methods are that the sequential solution method maintains and solves the equations of the DC system separately from those of the AC system but in the unified method, the equations describing the various DC systems' components are incorporated with the equations of the AC system and the collective set of equations of the AC-DC systems is simultaneously solved [2-3].

Similar to AC distribution networks, due to the large number of PQ buses and high r/x ratio, methods such as Newton Raphson and FAST Decoupled cannot be used in these systems; introduced methods, such as Modified Newton Raphson and Broyden approaches also cannot be used in AC/DC distribution networks.

In this paper, load flow calculations are studied in AC/DC distribution networks including a weakly mesh, in the presence of distributed generation sources and energy storage units, considering different converter control strategies, by backward forward sweep and compensation-based algorithms.

CONVERTER MODELLING

For the analysis of the steady state converter operation, some basic and generally valid assumptions can be made. Firstly, the AC voltages at the terminal buses are perfectly balanced and sinusoidal. Thus, a perfect AC filtering of all harmonic currents and voltages generated by the converters is assumed. Correspondingly, a perfect filtering on the DC side too is assumed and the DC current and voltage contain no AC components. Furthermore, the losses and magnetizing admittance of the two-winding converter transformers are ignored [2]. The objective of a converter station is to convert power from AC to DC when it is operated in rectifying mode and from DC to AC when it is operated in inverting mode [3]. The model of a converter station connected to an AC bus is shown in figure 1.

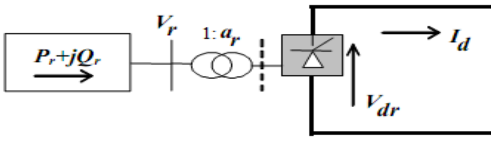

Fig.1 Converter modelling

The variables in Fig. 1 are defined as follows:
V_r = primary line-to-line ac voltage (rms)
V_d = direct voltage
I_d = direct current
a = transformer ration
P, Q = active and reactive power

The basic converter equations, for both rectifier and inverter operations, describing the relationship between the AC and DC variables can be written as follows [2-3].

A. Rectifier Equations

$$V_{dor} = k a_r V_r \tag{1}$$

$$V_{dr} = V_{dor} \cos\alpha_r - R_{cr} I_d \tag{2}$$

where V_{dor} is the ideal no-load direct voltage, $k=3\sqrt{2}/\pi$, and α_r is the ignition delay angle. R_{cr} is the so called equivalent commutating resistance, which accounts for the voltage drop due to commutation overlap and is proportional to the commutation reactance, $R_{cr} = 3X_{cr}/\pi$. The active power at the rectifier is given by:

$$P_{dr} = V_{dr} I_d \quad (3)$$

Since losses at the converters and transformers can be ignored, the reactive power at the rectifier can be determined as:

$$Q_r = P_r \tan\phi_r \quad (4)$$

where ϕ_r is the phase angle between the AC voltage and the fundamental AC current and by neglecting the commutation overlap can be calculated as:

$$\phi_r = \cos^{-1}(V_{dr}/V_{dor}) \quad (5)$$

B. Inverter Equations

The inverter operation of a converter can be correspondingly described by following equations:

$$V_{doi} = k a_i V_i \quad (6)$$

$$V_{di} = V_{doi} \cos\gamma_i - R_{ci} I_d \quad (7)$$

$$P_{di} = V_{di} I_d \quad (8)$$

$$Q_i = P_i \tan\phi_i \quad (9)$$

$$\phi_r = \cos^{-1}(V_{dr}/V_{dor}) \quad (10)$$

where γ_i is the extinction advance angle.

There are a number of different modes in which a converter station can be operated, for example constant current or constant power. The control modes of converter station are classified as follows [2-3].

1- Specified converter transformer tap
2- Specified DC voltage
3- Specified DC current
4- Specified minimum firing control angle
5- Specified DC power

BACKWARD-FORWARD SWEEP ALGORITHM

In this paper, load flow calculations in AC/DC distribution networks have been done by backward-forward sweep algorithm. First, in the backward phase, assuming flat voltage (1^{pu}) at all nodes, node currents are computed. Then, branch currents from end of the feeder to substation are determined during the DC network using KCL laws and inverters control strategies that connected to the loads. Then, the currents in AC branches are computed by using the rectifier equations, converter control strategy and the KCL laws. In the forward phase, with assuming one per-unit voltage at the substation, other nodes voltage can be calculated by using computed branch currents in pervious phase, and consideration of rectifiers and inverters control strategies. This process is repeated until the difference in node voltages of successive iterations is lower than the desired tolerance [4-5].

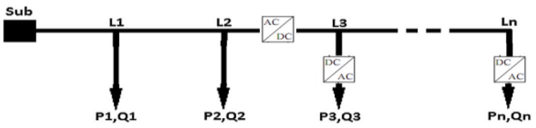

Fig.2 Illustrative example for backward- forward sweep algorithm in AC/DC distribution network

COMPENSATION METHOD FOR PV NODES

Distributed generators are classified as constant PQ or PV nodes. For PQ units, the models are identical with constant power load models, except that the current is injected into the bus. For PV units, the connected bus is modeled as a PV node. If the computed reactive power generation Q_{ig} is out of the reactive generation limits, then the reactive power generation is set to that limit and the unit acts as a PQ node. Some energy storage units may also act as a constant current node but for purposes of the load flow the PQ model is adequate [5-6].

If PV units are connected to AC network, then we use a compensation method using a PV node sensitivity matrix to eliminate the voltage magnitude mismatch for that PV node. The basic idea of the method can be explained as follows. Suppose a power flow as described earlier has converged, and the voltage magnitudes at PV nodes are not equal to the scheduled values. In order to obtain the scheduled voltage magnitude at a PV node, we need to determine the correct amount of reactive power or reactive current injection generated by the unit. Therefore, the problem of compensating PV node voltage magnitude becomes: Find the reactive current injection, I_q for each PV node so that the voltage magnitude, |V|, of this node is equal to the scheduled value. Since the relation between I_q and |V| is nonlinear, I_q can only be determined iteratively [6-7]. A PV node sensitivity matrix is introduced to approximate the nonlinear relation between I_q and |V| and is used to evaluate I_q iteratively as described below.

The incremental relation between the voltage magnitude and the magnitude of the reactive current injection is expressed as

$$[Z_V][I_q] = [\Delta V] \quad (11)$$

The dimension of $[Z_V]$ is equal to the number of PV nodes that connected to network. The diagonal entry, z_{ii} in $[Z_V]$ is equal to total impedance of all line sections between PV node i and the root node (substation bus). If two PV nodes, i and j, have completely different path to the root node, then the off-diagonal entry z_{ij} is zero. If i and j share a piece of common path to the root node, then z_{ij} is equal to the total impedance of all line sections on this common path. Further information about compensation method is available in reference [6-7].

Then, computed reactive power, Q_{ig} is compared with the reactive power generation limits. If Q_{ig} is within the limits then the corresponding reactive current, are injected to PV node i and in subsequent iterations, these currents will be combined with other nodal current injections. Otherwise, if Q_{ig} violates any reactive power generation limit, it will be set to that limit, and combined with the reactive load at this node. Subsequently, the row and column in the PV node sensitivity matrix, $[Z_V]$, corresponding to this node are removed and the $[Z_V]$ are updated [7-8].

If PV units are connected to DC network, in order to obtain the PV node scheduled voltage magnitude, we need to determine the correct amount of active power or active current injection generated by the unit. Therefore, the problem of compensating PV node voltage magnitude that connected to DC network, becomes: Find the active current injection, I_p for each PV node so that the voltage magnitude, |V|, of this node is equal to the scheduled value.

A PV node sensitivity matrix is used to evaluate I_p iteratively.

The incremental relation between the voltage magnitude and the magnitude of the active current injection is expressed as

$$[Z_V][I_p]=[\Delta V] \tag{12}$$

But for PV nodes that connected to DC network, the diagonal entry, z_{ii} in $[Z_V]$ is equal to total resistance of all line sections between these PV nodes and the rectifier node that DC network begins with it and considering its control strategy. Behind the works are similar to reactive current calculation for PV nodes that connected to AC network.

COMPENSATION FOR WEAKLY MESH

In this study, weak mesh can be divided into three modes and can be existed in AC network, DC network and between ac and dc network. In cases one and two, weakly meshed system is converted to a radial network by breaking all loops at breakpoints. Then, breakpoint impedance matrix Z_B should be constructed. In Z_B, the diagonal elements are the sum of the impedance (resistance in DC network) of lines which form the loop connecting the two buses of a breakpoint and the off-diagonal elements are the sum of the impedance in common lines for two breakpoint loops [4-5]. After performing backward current and forward voltage sweep iterations, for a breakpoint j, which is separated into two end nodes, j1 and j2, breakpoint voltage mismatch ΔV_B is calculated by equation (13).

$$\Delta V_{B,j}=V_{j1}-V_{j2} \tag{13}$$

If the maximum breakpoint voltage mismatch is greater than the breakpoint voltage convergence criterion, breakpoint current injection J will be updated using (14) and (15). For a breakpoint j, current compensation $-J_j$ is injected into end node j1, and current compensation J_j is injected into end node j2 [4-6].

$$Z_B\Delta J=\Delta V_B \tag{14}$$

$$J=J+\Delta J \tag{15}$$

In case 3, a converter links AC and DC networks and creates a loop. With regard to converter control strategy, we can break loop and convert the weakly mesh network into radial network. In this case, breakpoint impedance matrix Z_B is not needed and not calculated. Power transmitted through this link is calculated with considering converter control strategy and is injected into end nodes. In each iteration of backward forward sweep algorithm, this process will be done. For example, if mentioned converter control strategy is be constant power, so in each iteration of backward forward algorithm, this constant power injected into end nodes of the break point and should be constant. Then, branch currents are calculated based on these injected powers. This process is repeated until desired convergence criteria are reached.

LIST OF PARAMETERS

On each ac bus, there are four parameters – the voltage magnitude and angle, and the injected real power and reactive power. With two parameters known, the other two can be determined. On each dc bus, there are two parameters – the voltage and the real power. With one parameter known, the other one can be determined [2-3]. A list of parameters is provided in table 1, with the following notation.

$|V|$, δ: voltage magnitudes and angles respectively
P, Q: real and reactive power injections respectively
$|I|$: current magnitudes

Table 1. A list of parameters in AC/DC power systems

AC Buses	Bus Types	Known Parameters	Unknown Parameters
Substation	Slack	$\lvert V_{sub}\rvert$, δ_{sub}	P_{sub}, Q_{sub}
Generation	P|V|	$\lvert V_{ac}\rvert$, P_{ac}	Q_{ac}, δ_{ac}
Load	PQ	Q_{ac}, P_{ac}	$\lvert V_{ac}\rvert$, δ_{ac}
Diode Rectifier	P|I|	P_D, $Q_D(\lvert I_D\rvert)$	$\lvert V_D\rvert$, δ_D
Thyristor Converter	P|I|	P_T, $Q_T(\lvert I_T\rvert)$	$\lvert V_T\rvert$, δ_T
DC Buses	Bus Types	Known Parameters	Unknown Parameters
Generation	V	V_{dc}	P_{dc}
Load	P	P_{dc}	V_{dc}
Diode Rectifier	V	$V_{D,dc}$	$P_{D,dc}$
Thyristor Converter	V	$V_{T,dc}$ (dc voltage control)	$P_{T,dc}$
	P	$P_{T,dc}(I_{T,dc})$ (dc current control)	$V_{T,dc}$
		$P_{T,dc}$ (dc power control)	$V_{T,dc}$

RESULTS

Hypothetical AC/DC distribution network is obtained by little modifications on IEEE 33-Bus distribution system. Two rectifiers, one distributed generation and one energy storage unit are added to IEEE 33-Bus distribution system. This AC/DC distribution network is shown in figure 2.
Line and load data are available in []. Base power and base AC voltage are assumed 100 MVA and 12.66 kV respectively and base voltage for DC network is obtained by using rectifier equations. Table 2 shows rectifiers, distributed generation and energy storage locations and characteristics. Load flow results are shown in table 3. DG production is obtained 110 kW. Also, comparison of bus voltage magnitude for AC/DC distribution system including one mesh, one energy storage and one DG and with all of them is shown in figure 4.

Table 2. Locations and characteristics of rectifiers, DG and ES

	Rectifier 1	Rectifier 2
Bus Number	Between 5 and 6	Between 25 and 18
Commutation reactance [pu]	0.0459	0.0518
Minimum control angles[degrees]	$\alpha_{min}=7$	$\gamma_{min}=7$
Transformer regulation range	±15%	±15%
Control strategy	Constant voltage $V_{DC}=1$ p.u.	Constant current $I_{DC}=0.002$ p.u.
	Location	Characteristic
DG	On node 14	$V_{DC}=0.99$ p.u.
ES	On node 29	$P_{DC}=0.0006$ p.u.

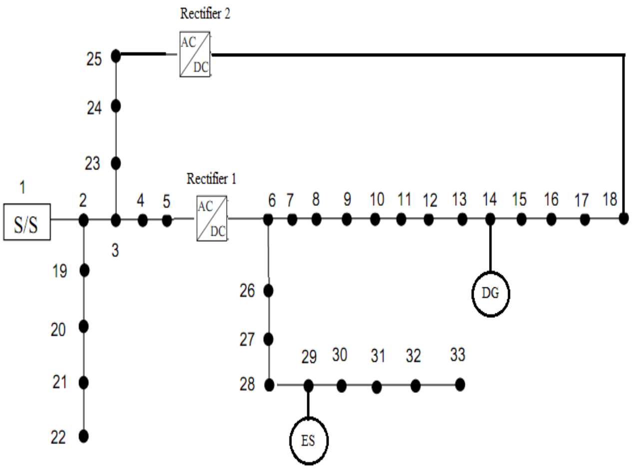

Fig. 3. Tested AC/DC distribution network

Table 3. Tested network bus voltage

Bus	Voltage	Bus	Voltage
1	1.0000	18	0.9891
2	0.9976 - 0.0005i	19	0.9971 - 0.0006i
3	0.9865 - 0.0027i	20	0.9935 - 0.0018i
4	0.9814 - 0.0043i	21	0.9928 - 0.0021i
5	0.9766 - 0.0060i	22	0.9921 - 0.0025i
6	1.0000	23	0.9826 - 0.0034i
7	0.9994	24	0.9753 - 0.0052i
8	0.9954	25	0.9714 - 0.0063i
9	0.9937	26	0.9994
10	0.9923	27	0.9986
11	0.9920	28	0.9958
12	0.9916	29	0.9939
13	0.9904	30	0.9928
14	0.9900	31	0.9914
15	0.9896	32	0.9911
16	0.9894	33	0.9910
17	0.9891		

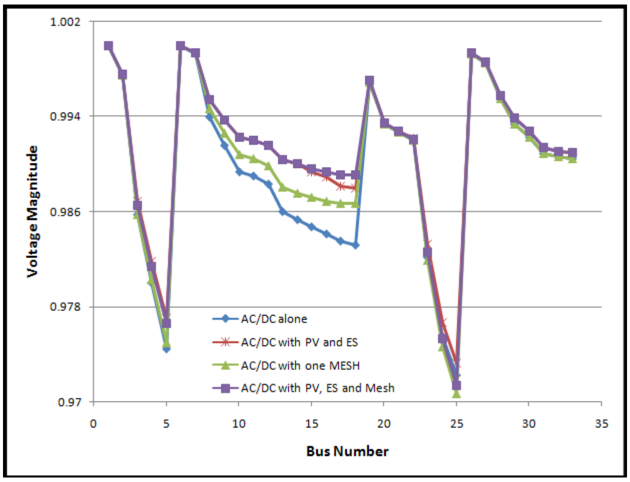

Fig 4. Voltage magnitude for different modes

CONCULUSION

In this paper, load flow calculations are studied in AC/DC distribution networks including a weakly mesh, in the presence of distributed generation sources and energy storage units, considering different converter control strategies, by backward forward sweep and compensation-based algorithms. The proposed algorithm is tested on hypothetical network by using MATLAB software. Simulation results show that by utilization of power electronic converters, voltage profiles can be improved.

REFERENCES

[1] J. Lassila, T. Kaipia, J. Haakana, J. Partanen, and K. Koivuranta, 2009, "Potential and strategic role of power electronics in electricity distribution systems," in *Electricity Distribution, CIRED, The 20th International Conference and Exhibition*, pp. 1-1.

[2] Osaloni, O.; Radman, 2005, "Integrated AC/DC systems power flow solution using Newton-Raphson and Broyden approaches," *Proceedings of the Thirty-Seventh Southeastern Symposium on*, vol., no., pp. 225- 229.

[3] Panosyan, A.; Oswald, B.R., 2004, "Modified Newton-Raphson load flow analysis for integrated AC/DC power systems," *Universities Power Engineering Conference, UPEC 2004. 39th International*, vol.3, pp.1223-1227 vol. 2.

[4] Shirmohammadi, D.; Hong, H.W.; 1988, Semlyen, A.; Luo, G.X.; , "A compensation-based power flow method for weakly meshed distribution and transmission networks," *Power Systems, IEEE Transactions on* , vol.3, no.2, pp.753-762.

[5] Cheng, C.S.; Shirmohammadi, 1995, "A three-phase power flow method for real-time distribution system analysis," *Power Systems, IEEE Transactions on* , vol.10, no.2, pp.671-679.

[6] Rajicic, D.; Dimitrovski, 2001, "A new method for handling PV nodes in backward/forward power flow for radial and weakly meshed networks," *Power Tech Proceedings*, vol.3, no., pp.6 pp. vol.3.

[7] Zhu, Y.; Tomsovic, 2002, "Adaptive power flow method for distribution systems with dispersed generation," *Power Delivery, IEEE Transactions on*, vol.17, no.3, pp. 822- 827.

[8] Jen-Hao Teng; Chuo-Yean Chang; , "A novel and fast three-phase load flow for unbalanced radial distribution systems," *Power Systems, IEEE Transactions on* , vol.17, no.4, pp. 1238- 1244, Nov 2002