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A new backward/forward method for solving radial distribution networks with PV nodes

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Abstract

In this paper, a new backward/forward (b/f) methodology for the analysis of distribution systems with constant power loads is presented. In the proposed method, at each iteration, the loads are considered as constant impedances; in the backward sweep all the network variables (bus voltages and branch currents) are evaluated considering a scaling factor which is determined at the end of the backward phase. Indeed the forward sweep is eliminated and the node voltages calculation does not demand the sequentiality needed in the b/f methodology. The developed method, although deriving conceptually from the b/f methodology, presents only the backward phase in which all the network variables are evaluated considering a scaling factor. Moreover the load simulation as impedances is particularly important when the network shows PV nodes for which the voltage displacement and the reactive power are the unknowns. The condition of 90° displacement between the PV node voltage and the current injected by the apparatus for voltage regulation is not usually satisfied in networks solved by methods using constant current load models. The possibility to solve, at each iteration, a network made up of impedances allows to evaluate the reactance that must be inserted into the PV node in order to set the voltage at the prescribed value. In this way the value of this reactance is updated at each iteration and, at the end of the iterative process, whatever it is the displacement of the PV node voltage, the current circulating into the voltage regulating apparatus will be at 90° from it. In the paper, after a description of the PV nodes models reported in the b/f analysis literature, the new method is presented. The way in which the constant power loads are represented by means of a constant impedance model is also illustrated as well as the method for the evaluation of the unknown reactance to be installed at the PV nodes. The results of the executed applications show the efficiency of the model in terms of precision in the calculation of the reactive power required to sustain the voltage at the PV nodes.

Keywords: Radial distribution networks; Backward/forward method

1. Introduction

In some cases the classical Newton–Raphson (NR) method in the radial distribution analysis can show difficulties; for this reason specific methodologies have been developed for these kinds of electrical systems. The NR approach, considering some modifications based on the particular features of the radial structure, has been applied in [1], where the load flow equations are written in terms of new variables resulting in a set of $3N$ equations for a network with $N+1$ buses. As $2N$ equations are linear and N are quadratic, a computational scheme, based on the NR method, is developed in order to increase the efficiency of the methodology.

For constant power loads or mixed loads, with a constant power component, the analysis method more frequently adopted in radial distribution systems, is the iterative backward/forward (b/f) methodology. Three different methods exist in the b/f methodology: the current summation method, the power summation method and the admittance summation method.

For the current summation method, each iteration is fundamentally articulated in two steps. In the first phase (backward phase), on the basis of a known voltage profile, the load currents derived from the loads and from the capacitive admittances of the lines are evaluated and, from these, starting from the terminal branches and going towards the source node, the currents flowing in all the system's branches are determined. In the second phase (forward phase), starting from the source node and going towards the terminal nodes, the voltages at all nodes are calculated. Once the iteration is ended, for each node, the starting and ending values of the voltage are compared; if, for all the

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nodes, the difference is below a fixed value, the iterative process stops. Otherwise, another iteration is performed and, based on the nodal voltage and on the power of the loads, new values of the currents required by the loads are evaluated.

For the power summation method the procedure is similar with the obvious difference that, in the backward sweep, the branch power flows are evaluated.

In the admittance summation method the loads are simulated, in each iteration, by means of admittances; in the backward sweep, starting from terminal nodes, the driving admittances of each node are determined; once determined the source node driving admittance, it is possible to evaluate the total current requested from the system; in this way, during the forward sweep and starting from the source node, the bus voltages can be calculated. It can be noticed that in the traditional b/f methodology, any is the load simulation, the node voltages determination must be executed sequentially, i.e. the voltage calculation of a bus necessary requests the evaluation of the voltages of all upstream nodes.

If the network is meshed, the system can be turned into radial executing a number of cuts in the branches (cuts number is equal to the number of independent meshes) and introducing, for each cut, a new unknown which is the current to be injected between the two nodes created by the same cut so as to equal the voltage at the same two nodes. The calculation of this current is performed using the multi-port compensation method presented by Tinney [2]. The introduction in distribution systems of small dispersed generation units requiring by the system the reactive power necessary to sustain the voltage at the same nodes implies that it is necessary to set distribution systems analysis methods where PV nodes can also be included. These nodes inject in the system a fixed value of active power at a given fixed voltage, the reactive power at these nodes is the unknown as well as the voltage displacement. The presence of PV nodes is considered in [3] within a power flows calculation method valid for slightly meshed distribution and transmission systems; at each iteration, the PV node voltage is modified giving it the fixed value and its displacement is equal to that calculated for the voltage at the same iteration. The reactive power at the same node necessary to keep the voltage at the same node at the required value is calculated with the secant technique using the voltage values at the same node calculated in the two preceding iterations. The methodology used to turn into radial the meshed systems is also followed in [4] to consider the PV nodes; a mesh between the reference node and the PV node is created, then into this mesh a voltage source with the same prefixed value for the PV node is inserted. The mesh is opened through a cut and the reactive power that must be injected to set to zero the voltage difference between the PV node and the voltage source terminal is injected. The reactive power is then updated at each iteration on the basis of a sensitivity matrix which, under the hypothesis that all nodes have voltage magnitudes close to 1 p.u. and negligible relative displacements, is the same as the reduced equivalent impedances Thèvenin matrix. The methodology just described is recalled and modified in [5] in order to speed up the convergence. At the end of each iteration, and before the update of the currents values, the nodal voltages are corrected considering that in the network there are only the compensation currents variations, both in the cuts representing real meshes and in the cuts performed on fictitious meshes (PV nodes). A three phase power flow based on the methodology developed in [3], is presented in [6] to solve meshed distribution systems with dispersed generation (PV nodes), unbalanced loads, voltage regulators and shunt compensation banks. For the same type of network, the just mentioned methodology is applied in [7] to evaluate the currents due to different permanent fault conditions; a hybrid Thèvenin equivalent impedance matrix links the compensation currents of the real meshes with those of the fictitious meshes related to the PV nodes and to the faults with the relevant voltage differences. In [8] the method presented in [5] is again considered with some modifications in the calculation of the compensation currents of the PV nodes made in order to ensure that, at each iteration, the current to be injected into the PV nodes is at 90° with the nodal voltage. A different approach, but still belonging to the compensation currents methods family, is presented in [9] where the calculation of the unknown quantities for the PV nodes is performed at the end of the backward phase on the basis of the distribution of the currents in the branches upstream the PV nodes. A suitable sequence in the solution method for the calculation of the currents in the real and fictitious (PV nodes) meshes, as well as the update of the currents in the branches after the calculation of each of these currents, allow the reduction of the errors and thus to accelerate the reach of the solution. In [10] for the fictitious meshes related to the PV nodes, the compensation currents are deduced by means of a sensitivity matrix and of the voltage differences existing between the cut nodes, whereas the voltage on the network side is known in phase and magnitude at the end of each iteration and the voltage on the ideal generator side is known only in magnitude, the latter being equal to the specified value for the PV node. The phase of this voltage is deduced imposing that the power injected in the system is only reactive power; thus, once the forward phase is ended, first the calculation of the displacements of the voltage phasors to be associated to the PV nodes ideal generators is performed, then, the calculation of all the compensation currents through the reduced equivalent Thèvenin impedance matrix is carried out.

In this paper, the network is solved considering, at each iteration, the loads as impedances; in the backward phase, the currents circulating in the impedances derived from the terminal nodes are arbitrarily chosen, then the voltage at the source node is calculated considering a passive network of impedances; the ratio between the voltage imposed at the source node and the one just calculated at the same node is the correction factor which allows to calculate the actual values of bus voltages, loads currents and branch currents. Then, for each PV node, the value of the reactance for which the bus voltage magnitude gets a prefixed value is calculated. Such value is modified in the subsequent iteration since the loads impedances vary due to the bus voltage changes.

The new methodology shows advantages such as the absence of the forward phase, the possibility to set a convergence criterion based on the evaluation of the error in the calculation of the voltage only at the source node at the end of the backward phase