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A model for reactive power tracing by addition of fictitious nodal injections

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ABSTRACT

This paper proposes an efficient solution to the problem of reactive power flow tracing in electrical transmission networks. For such systems, the tracing techniques used for active power flows cannot be used straightforwardly, due to reactive power variations induced by the line reactances, these variations often being comparable to the powers delivered to the loads. In other words, as is well known, in transmission systems the reactive flows are strongly influenced by the inductive and capacitive effects of the network, making the tracing of power flow and allocation of losses more critical. In this paper, after discussing some methodological aspects, an approach based on the use of transmission line models differentiated on the basis of the reactive behaviour of the lines is proposed. These models allow the power contributions due to reactive losses to be evaluated separately and compared to the flows exchanged between generators and loads; moreover, their application does not require the introduction of nodes or additional links, as is the case with other methods proposed in the literature. The proposed tracing technique is then presented; the method is straightforward and does not require the creation or inversion of matrices of participation factors. The paper concludes with two applications, a 4 node system and the IEEE test system with 30 nodes.

1. Introduction

The technical literature on the problem of reactive power flow tracing is not so large. A large part of it concerns active power flow tracing and this focus on active flows is due to the economic implications of such tracing problems. In many papers, the methodologies set up for active flows are said to be just as suitable for reactive flow tracing. Such statements, although valid in many cases, are not true in general; indeed, for transmission systems, the physical behaviour of the lines must be considered. As clearly evidenced by Bialek [1,2], as far as reactive flows are concerned, the lines can be considered to be sources or sinks; this is very different from the behaviour of active power flows for which the lines are always simple ‘carriers with losses’.

Taking into account the losses, both as a generator or consumer of reactive power, it is fundamental to correctly carry out the tracing of reactive power. Only for power distribution systems, or for heavily loaded transmission systems, can the methodologies developed for active power flow tracing be extended to reactive power flow tracing. In [1] and [2], based on the principle of proportional sharing, Bialek elaborates a methodology for evaluating the power delivered to each generator, to each load and the division of power flows along the lines among generators and loads. The method set up specifically for active powers, is suitably modified to extend it to reactive power flow tracing. In this case, due to the reactive power losses in the lines, it is not possible to make any of the assumptions that are valid for active power. To overcome this problem, Bialek introduces, in each line, a fictitious loading or generation node (considering the physical behaviour of the line with reference to reactive power). In this way, the system is changed so that it is possible to apply the methodology already set up for active power flows; in the latter case, the tracing procedure implies the inversion of a matrix of order at last equal to the number of nodes of the network; therefore, in the case of reactive power flow tracing, the order of the matrix becomes equal to the summation of the number of nodes and of the number of lines. In [3], a methodology for active power flow tracing is outlined; the authors say that such methodology is also suitable for reactive power tracing; but the applications only concern active power flow tracing.

To avoid problems deriving from the non linear coupling between active and reactive flows due to losses in the lines, in [4] all the power injected in the nodes and lines and the power required by the loads are turned into real and imaginary currents. Starting from the generation nodes, the currents are partitioned among the loads. In this way, the total current injected by the generator is divided among the loads of the system; knowing the current supplied by the generator to a load, the relevant active and reactive powers are evaluated at the generation node. The difference between these powers and those of the loads are the active and reactive power losses to be given to the load. When tracing the power flows from generators to loads, the use of currents instead of powers prevents a power loss partition policy from being applied; indeed, the

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allocation of losses to loads depends on the load current and on the voltage drop between the load node and the generation node from which the load current comes. Such a voltage drop depends, not only on the particular load current, but also on the other currents circulating in the same path; these currents can be caused both by other loads and by the behaviour of the network. If the tracing is based on power flows, the losses can be calculated line by line and partitioned, according to some predefined criteria, among the different components of the power flows.

A method based on the nodal generation of distribution factors is developed in [5]; in this way the contribution of the generators to the real and reactive powers required by the loads is evaluated. A graph theory is applied in [6] to solve the problem of active power flow tracing; the methodology is claimed to be suitable for reactive power flow tracing. The power losses in the lines are given to one of the end buses in each line. If some power is injected at one of the two end nodes of a line, the two injections are treated as loads at the two nodes and the line is considered to be open circuit.

The methodology developed in [1] is again considered in [7] for reactive power flow tracing in networks having convection lines, namely lines in which the reactive flows at the two ends have opposite directions; for these lines, an equivalent nominal-T line model replaces the nominal-π model. At the central node, a fictitious reactive load is considered, it is equivalent to the summation of the reactive powers required by the shunt admittances of the nominal-π model. The original system modified in this way is solved a second time and the results of the latter load flow are used for reactive power tracing.

The mutual influence between active and reactive flows in the lines through the losses is dealt with in [8] where, for each line, the total differential of the active loss and its components (the partial differentials) are determined. Starting from these differentials, the complex power flows are determined on each line as the summation of components – allocated at the single generators – both of the powers sent to the loads and of the losses. The implementation of the methodology and the results of some applications are reported in [9].

A technique based on the construction of a matrix of participation coefficients of the nodes to the flows on the afferent lines is developed in [10]; the method applies both to real flows and to reactive flows; the power losses in each line associated with a single component of flow are proportional to the entity of the same flow.

In this paper, the critical issues of reactive power tracing (Section 2) and some methodological aspects of the problem (Section 3) are first discussed. Then, an approach based on the use of transmission line models that are based on the reactive behaviour of the lines (Section 4) is outlined. The models allow the separate evaluation of the contribution of power due to reactive losses, without needing to introduce fictitious nodes or branches. The technique is simple and straightforward and is outlined in detail in Section 5. To illustrate the easy applicability and usefulness of the method, in Section 6, a simple application and a comparison of the method with that proposed by Bialek in [1] and [2] are shown. Finally, after having reported in Section 7 the results of an application to the IEEE 30 bus test system, in Section 8 are summarized the main positive features of the proposed methodology.

2. The tracing problem for reactive power flows

The various techniques proposed in the literature for power flow tracing are primarily aimed at active flows and are based on the following general assumptions:

- in each line, the losses are much smaller than the power flow; therefore the two starting and arriving flows always have the same direction; moreover, since the values of the two flows are only slightly different, the relevant participation coefficients of the generators (loads) do not show large variations;
- the active power losses can be delivered entirely either to the generators or to the loads, neglecting, in the allocation process, the dependency of power losses on shunt conductances via the bus voltages.

These assumptions, which are valid for all electrical systems that are correctly designed and operated, lose their general validity when the reactive power flow tracing problem is considered. The problem is mainly present in HV transmission networks, where the reactive flows depend strongly on the inductive and capacitive effects of the network: each line on the basis of its own physical features and in relation to the power flow (which can be smaller or larger than the natural power of the transmission line) introduces reactive power variations that may become comparable with those delivered to the loads. In other words, each line behaves as a generator (load) injecting reactive power that is not negligible compared to the power flows in the network. In some cases, this behavior can cause the presence of reactive flows at the two ends of a line that are both outgoing or entering the line (convection lines).

Another critical aspect concerns the connection between real and reactive power flows. Since the losses in the resistance and reactances of the longitudinal lines vary with the square of the current and, then, with the square of the apparent power, the real and reactive power tracing problems are actually a unique problem and they should be solved simultaneously. But, due to their non linearity, it is not possible to unequivocally divide the losses (real and reactive) among the generators or among the loads connected to the network; and the problem is mathematically undetermined. Only introducing the simplifying hypothesis that real (reactive) losses depend on real (reactive) power flows it is possible to reach as solution. The separate solution of the two tracing problems leads to solutions that are at best approximate for higher losses. In a transmission network, the presence of limited real losses allows the active flow tracing problem to be solved separately from the reactive one, without limiting the significance of the results. As the reactances of lines and transformers are higher, instead, the reactive flow tracing process becomes more sensitive to active flows.

For transmission systems, therefore, the problem of tracing reactive flows requires specific methodologies that take into account the contributions of the flow that are caused by the physical behavior of the network, also in relation to active power flows.

3. Some methodological aspects

The critical aspects of the reactive tracing problem summarized above can be overcome by suitably choosing the model with which each transmission line is represented in the solution of the tracing problem. If the adopted model allows the longitudinal flows to be traced separately with respect to the reactive loss contributions, the problem of the dependency on active flows can be overcome.

As already pointed out, indeed, such a dependency is caused by the mutual terms in the loss expression. The latter, if evaluated separately, can be shared among the generators (or the loads) in the next phase. These terms can also be calculated as a function of the active flows and using different criteria for their attribution.

In this respect, the approach proposed in [1] appears interesting. It introduces, in each line, a fictitious node (load or generation, based on the reactive behavior of the line) at which the power injection is equal to the reactive losses of the upstream line.

The method [1] has the following advantages: