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New reactive power flow tracing and loss allocation algorithms for power grids using matrix calculation

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ABSTRACT

A novel simple method is suggested in this paper to evaluate the contributions of the sources (including the generators and branches' charging capacitances) or the loads to the branches' reactive flows and losses separately as well as to calculate the sources' shares in providing the loads' reactive powers. In the method, the study system is first converted to the system, each branch of which only has reactive loss, using a new technique for modeling the generating branches based on the AC load flow results. The properties of two new matrices (i.e. injection-bus and absorption-bus matrices), which are constituted for the obtained system, are then used to derive three other matrices. These matrices, which express reactive power productions of the sources in terms of reactive power consumptions of the demands (viz. the loads and branches' losses) and vice versa, contain the intended contributory factors. Three-bus system is applied to demonstrate the computing process of the method whereas several IEEE systems are used to show its capability to implement on the transmission systems with arbitrary topologies and sizes. Some advantages of the method compared to the earlier methods are also illustrated.

1. Introduction

With the trend toward the deregulation of the electric power industry, the allocation of the transmission service cost to the users in an equitable and reasonable manner becomes much more significant. To ensure fair calculation of the price of all power wheeling transactions in this new competitive environment, it should be needed to know how each market participant utilizes the transmission network. This information can be determined only when the paths of delivering the powers from the sources to the loads and their amounts are assessed by power flow tracing. However, it is very difficult to answer the question 'what fractions of the given branch flow and loss are attributed to a particular source or load?' in a nonlinear power system. Thus, one complicated issue that has attracted many researchers is finding the widely accepted solution for power flow tracing problem.

Since the direction of the reactive power flow incurred by the selected source through the specified branch may not be the same as the direction of the active power flow, power flow tracing should be accomplished separately for active and reactive power [1]. Because the main commodity traded in the present day electricity markets is active power, a large part of the technical literature focus on active power flow tracing and the methods developed in some of them are said to be applied straightforwardly to trace the reactive power flows. In general, this statement is not correct because the branches always waste active power, whereas they can be considered to be both producer and consumer of reactive power due to their capacitive and inductive behaviors [2]. Owing to these facts and regarding the vital role of the reactive power in maintaining voltage at all buses of the system within limits and improving active energy transfer capability, there are the outstanding papers which emphasize on finding the shares of various sources in the reactive power flow and loss of each branch to identify that each source feeds which loads and how much. The methods presented in these papers can be broadly classified into three main groups:

(1) This kind of approaches assumes that the power flow coming into each bus contributes to all power flows leaving that bus the same as the proportion of its amount to the total inflow powers [1–13]. Although this assumption is intuitively logical, but its correctness can never be theoretically proved. This makes the validity of the application of these approaches to be doubtful.

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(2) Since these methods use the admittance (Y) or impedance (Z) matrix and the load flow equations directly to derive the sources and loads' participations in the transmission costs and losses [14–29], they pay more attention to the actual characteristics of the system and thus have a great advantage over the previous group of methods. In some of these methods [14–17], the basic circuit relations are combined with the game theory for the division of the branch power flow and loss among the generators and loads. To implement this type of methods, the storage of a huge amount of data and a considerable computational burden are often required. Therefore, they are inappropriate for real-time applications. Moreover, Refs. [14,15] obtain non-zero values for each generator's contributions to the reactive power flows of all branches. This issue does not seem reasonable, because the reactive power cannot actually flow to long distances from its producer. Refs. [16,17] suppose that the generating and demand buses have the same responsibility in the use of every branch and consequently half of the total costs or losses of the transmission system should be allocated to each class of buses. The lack of a physical and economic justification for this allocation ratio causes its specification to be arbitrary, which is not satisfactory for market participants. Refs. [18–22] also do not consider the generator as a supplier of reactive losses, notwithstanding they employ no predefined sharing ratio to split the reactive loss of each branch between the generators and loads simultaneously. In addition, since the effect of the branches' charging capacitances on providing the reactive loads and losses is not discussed in Refs. [17–20,23–25]; the reactive power produced by the charging capacitance of each branch is considered as a part of its reactive loss in Refs. [16,21,22,14,15,26,27] represent every branch by the series impedance and ignore the shunt admittances from its equivalent circuit model; these references do not take into account the charging capacitance as a reactive power source. Even though the reactive power production of the charging capacitance is accounted in Refs. [28,29] by integrating it with the end bus injections according to the π-equivalent circuit of the branch, but this modification may lead to a significant change in the system's topological features, which can influence the generators' contributions to some loads and branches' flows. Furthermore, negative loss allocation to a number of generators or loads is seen in Refs. [14–16,21,22,26]. This situation, which results in negative cost assignment, can be interpreted as cross subsidy and thus it is not allowable from an economics point of view.

(3) To enhance the computation time of evaluating the amount of the reactive powers transmitted from generators to loads, Refs. [30–32] apply artificial intelligence. In these references, the generators' shares in reactive loads obtained by the procedure belonging to the other two groups of methods, are used for training the neural network or support vector machine. However, the proper performance of these techniques is highly dependent on the training process, which must be repeated for every change in the system topology, and fine-tuning of their various parameters, which should be done by the heuristic optimization algorithms. In addition, the methods developed by these references in such a complicated manner cannot specify the contribution of each reactive source or load to the branch power flow and loss.

In this paper, two novel algorithms are proposed to determine the share of each source or load in the reactive loss of each branch. These shares are used for specifying the contributions of the sources or loads to the reactive powers at both ends of each branch. One of these algorithms can also calculate the participation of each source in the reactive power consumption of each load. To consider the charging capacitance of each branch as an independent reactive power source and take reactive losses into account directly in the course of the algorithms, the new model, which is developed based on AC load flow solution, is applied for representing the branches. Therefore, neither embedding reactive power productions of the charging capacitances into the nodal powers nor adding more virtual buses and branches to make the system lossless is required in the proposed method. Instead of the proportional sharing assumption, the method employs algebraic and physical meaningful equations to obtain non-negative quantities for the sources and loads responsibilities in reactive losses; thus, not only the existence of cross-subsidies is avoided, but also the relative locations of the sources and loads within the system are reflected in the allocation result.

The proposed technique for acquiring a proper model of a branch is introduced in the next section. Afterwards, the above-mentioned algorithms are described in detail. Subsequently, the procedure of implementing the method is illustrated using a simple example system, and its capability to trace reactive power flows in any system configuration is shown by applying it to different standard test systems. Additionally, the method is compared with the previous ones to demonstrate its merits. Finally, conclusions are discussed.

2. Proposed model for representation of system branches

In the proposed method, a branch connects two buses of the system; thus, each line or transformer is considered as a branch. In addition, a source produces reactive power in the system; hence, a generator or branch can be regarded as a source. It is to be noted that in the circuit model of each branch, the charging capacitance does not exist, but there is the inductance; so, some of branches play the role of a source, while all branches have reactive loss. Therefore, if the number of the system branches is N_L and the number of the branches, which also generate reactive power, is N_C, it can be written: $N_C \leqslant N_L$.

To trace the reactive power productions of the branches by the proposed algorithms, the generated reactive power of each branch, which is computable after executing the AC load flow, is first modeled as a source on the independent fictitious bus. This bus is then connected to the end buses of the original branch by two fictitious branches. The reactive loss of each fictitious branch is assumed to be equal to one half of the reactive loss of the original branch. In other words, each generating branch is replaced with a bus and two branches; thus, the system obtained by this action has $(N_L + N_C)$ branches, none of which neither produces reactive power nor has bidirectional reactive power flows. Furthermore, if the main system has N_B buses, the obtained system will have $(N_B + N_C)$ buses. Fig. 1 shows the values of reactive powers come from the fictitious bus, which is denoted by N in a dashed-circle. In this figure, $\boldsymbol{Q_C}$ is the N_C-dimension vector whose elements are formed by reactive power productions of the generating branches of the main system, and the N_L elements of the $\boldsymbol{Q_{Loss}}$ vector are equal to the values of reactive losses of the main system branches.

3. Tracing the reactive power produced by sources

The first step of the proposed algorithm is the formation of the injection-bus matrix for the modified system considering the values of reactive power flows of its branches. This matrix is defined as: