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Reactive power cost allocation by power tracing based method

Mala De [*], Swapan K. Goswami

Jadavpur University, Kolkata, West Bengal 700 032, India

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ABSTRACT

A reactive power cost allocation method based on power tracing principle is presented here. A new solution is proposed to solve the problem of bidirectional reactive power flow to enable the application of power tracing method to reactive power flow. Reactive power supplied by the line charging capacitance is considered to be a separate reactive source and accordingly reactive load and loss are also allocated to it. Total system reactive demand including load and loss is first allocated to all the sources, viz. generators, synchronous condensers, capacitors and line charging capacitance and finally these sources are offered the revenue for supplying this power according to the pricing structure adopted. In the present work a quadratic reactive cost function is adopted for the generators and all other sources are considered to have a fixed cost per unit MVar supplied, which is calculated from the installation cost of the respective reactive power source. The work is demonstrated on IEEE standard test systems and a practical Indian grid system.

1. Introduction

As electric power industry move from monopolistic structure to unbundled competitive structure, there is a necessity for separately pricing each component of electricity, i.e. not only power generation, transmission and distribution, but also the pricing of ancillary services. Reactive power is regarded as an important ancillary service since it is essential for system security and voltage control. In conventional monopolistic power system the cost of reactive power support was normally recovered by two ways – by including the reactive support cost into the active power price or, using penalty based on load power factor [1]. But in deregulated environment a direct pricing method for reactive power is highly demanded as all the ancillary services including reactive power support must be priced separately and transparently for healthy market operation. Two types of reactive power pricing schemes are present in existing literature – OPF based spot pricing and power flow and graph theory based pricing. Some of these OPF based methods have also incorporated the effect of security constraints in terms of voltage limits [2] and MVA over-load limits in the OPF formulation [3]. Spot pricing of reactive power at any bus is determined by marginal cost of reactive power at that bus [4]. But the marginal cost has drawbacks like – volatility of price with a small change in system behavior and inability to recover total cost [5]. The second category i.e., power flow based cost allocation schemes use power tracing with proportional sharing [1,6,7], graph theory based [8–12] methods, modified Y-bus method [8–10] or voltage source equivalent model of generator [12] to allocate reactive power cost. The power tracing based methods generally use proportional sharing principle for allocating load/loss to a generator. These types of approaches determine the amount of reactive power produced by each generator for each individual load and then the loads are charged and the generators are paid accordingly. But the cross-coupling effect of reactive power flow makes the calculation of contribution of generators to load somehow inaccurate as it is dependent on some assumption.

Another OPF based option of pricing structure is nodal pricing. Here sensitivity of generation production cost to reactive power is determined and as the variable cost of reactive power production is very small and does not include the effect of high capital cost, this pricing structure is not effective [1,13]. Different practical power systems existing world-wide adopt different reactive power pricing strategies [14–16]. In some practical systems the reactive power cost is decided by taking a part from capacity payment and the other part from actual production cost of the reactive source [17]. Generally a higher importance is given on the capacity payment and a lower on actual production cost. Game theory is also applied for reactive power pricing [18] and very recently ant colony based search method is used for this purpose [19]. As OPF based reactive power pricing schemes are very often unable to recover the total reactive power cost, power tracing and power flow based pricing scheme is adopted in the present paper which is detailed in the next section along with its problems and proposed solution.

One very important fact in determining reactive power cost is – it has two distinct components; the production cost and the capital cost. The production cost is very small whereas the capital cost of is

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[*] Corresponding author. Tel.: +91 9434760646.
E-mail address: mala.de.gm@gmail.com (M. De).

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generally very high; therefore, reactive power cost must be related to capital cost. Another component of reactive power cost is the opportunity cost. If any generator is forced to reduce its active power production to supply reactive power due to its capacity limits, the generator should be compensated for this active power revenue loss which is called loss of opportunity cost (LOC).

In this paper, reactive power sources are first grouped into two broad categories and then two different pricing structures are decided for these two groups. The generators come into one group and all other sources like synchronous condensers, capacitors and line charging capacitances come under the other group. A quadratic reactive cost function is adopted for the generator which is derived from the active power quadratic cost function of the generators using the generator power factor [20]. Other sources are considered to have a fixed reactive power cost per unit MVar supplied; this fixed cost for capacitor is calculated from its installation cost. The cost of the reactive power due to line-charging capacitance is determined by the average system reactive per unit cost. These pricing structures are detailed in Section 3 followed by the application of the proposed method on test system.

2. Allocation based on power tracing

As discussed in the last section, there are two types of reactive power pricing methods present; based on OPF and based on power flow. The pricing schemes under the second category use mainly reactive power tracing and graph theoretic analysis to allocate the reactive power from a generator to a load. Though power tracing has proved to be an effective tool in case of active power, it very often encounters a serious problem in case of reactive power tracing as discussed below.

2.1. Problem in reactive power tracing

Power tracing involves moving along the power flow path from a terminal point, viz. load or generator, throughout the system following power flow result. To determine the contribution of any generator to the active power received by any load, it proves to be a good tool. But unlike active power flow, reactive power flow often involves bidirectional flow i.e., reactive power flows into a branch or out of a branch towards both the ends. The presence of this type of branch flows makes the application of power tracing impossible as the reactive power flow path discontinues at these branches. The problem can be explained easily using Fig. 1, which shows the active and reactive power flow directions through different branches of 6-bus system.

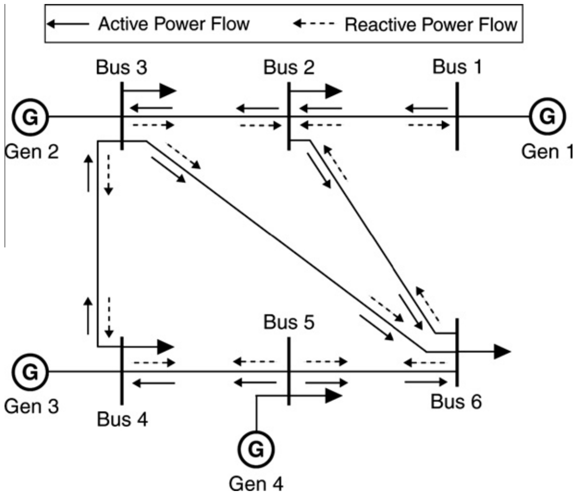

Fig. 1. Power flow result showing active and reactive power flow of 6-bus test system.

From Fig. 1 we see that active power can easily be traced throughout the system starting from any generator; e.g. Gen 1-bus 2–3–6 or Gen 4-bus 4–3–6, etc. But if we try to trace reactive power, we see that in branch 1–2 reactive power flows out of the branch from both ends and in branches 4–5 and 5–6 reactive power flows into the branch from both ends. Therefore, reactive power tracing cannot be applied to these branches. If we start reactive power tracing from say Gen 3, we are unable to do so as reactive power from this generator goes into branch 4–5 but there is no outward flow of reactive power, it again flows into the branch from opposite end. Similar problem will be encountered in case of reactive power tracing from any other generators. This problem makes reactive power tracing directly from power flow results, an impossible task; hence compared to active power tracing reactive power tracing becomes a complicated task.

2.2. General treatment of line reactive power

The above-stated problem is already dealt with in existing literature. In [1] the line losses are first moved to the end buses as loads to make the whole network lossless. If there is no circulating reactive power flow then the downstream and upstream tracing algorithm is applied directly to allocate reactive power contribution of generator to loads. But in presence of circulating flow these algorithms fail. Here the authors have introduced two lemmas which state that if circulating flow exists in a lossless network that means a phase shifting device or a voltage regulator is present there. The authors have further added that in any well-operated system, reactive power circulating flow should be avoided as it creates additional losses to the system and this can be avoided by proper transformer tap control. Downstream and upstream algorithm can be used once circulating power flow is eliminated by proper transformer tap setting. This method is a little complicated as one needs to go on changing the tap settings of the transformers till all circulating flows are eliminated. It may also not be possible always to remove all the circulating flows using this method for a large, complex system. In [21] authors propose a reactive power tracing method for pool based power system by introducing the hybrid genetic algorithm and least squares support vector machine (GA-LSSVM). The power tracing method is used as a teacher. To obtain a lossless system, the concept of virtual load is proposed. Prior to that, the equivalent transmission line model is introduced which integrates the nodal reactive power with the power produced by shunt admittances. Based on power-flow solution and reactive power tracing procedure by proportional sharing, the description of inputs and outputs for training and testing data is created. The generators' shares to reactive loads are determined by the proposed GA-LSSVM model.

Present authors propose a circuit theory based simpler solution to this problem. To explain the proposed method easily, we must try to realize the reason behind the problem. Transmission line has series inductive reactance and shunt line charging capacitance; the former one causes reactive power loss in the line and the later one works as a reactive power generator. The combined effect determines whether reactive power will flow in or out of a terminal of any branch. Depending upon the value of reactive power associated with these two components it may result into different situations described below.

Let reactive power loss due to line reactance is represented by Q_{loss} and reactive power supplied by the line charging capacitance is represented by Q_C as shown in Fig. 2a.

Let reactive power flowing into the branch i–j is Q_{in} and the amount flowing out of the branch is $Q_{out}\cdot Q_C$ for any branch i–j