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Contribution Analysis of Generator's Reactive Power as Ancillary Service

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1. Introduction

Traditionally, power system has been operated in view of balancing the demand and supply of real power. Cost functions of generators have been presented by the real power output of the generators and the operating point could be acquired by minimizing this cost functions. Recently, several power systems adopt the power market with real power market and ancillary service market. The economic operating point of real power market can be acquired by minimizing the generation cost which is almost same with the pre-market power system. However, the reactive power of a generator should be treated in different way with the pre-market power system because it should be paid in ancillary service market. The pricing technique for reactive power has been studied in several ways. First, the price of the reactive power can be defined by the concept of marginal cost. [1-3] The marginal cost of the reactive power is defined by the ratio of the cost variation and reactive power variation. If the reactive power output of a generator is changed, it makes the system loss altered so that the total generation cost become different. These methods evaluate the reactive power by the variation of active power generating costs caused by the reactive power. Julian Barquin Gil considered the reactive power as a commodity like active power market[4]. But, it is difficult to define the reactive power as a commodity since the value of reactive power is location-dependent and it is nearly impossible to transmit the reactive power in long-distance. K. Bhattacharya suggested the cost curve of the reactive power and the bid structure to maximize the profit of the ISO[5, 6]. However, the definition of a bid curve is not clear and several papers are reported to suggest the cost curve of the reactive power[6-8]. Optimal power flow techniques are adopted to include the opportunity cost and the installation cost of static condenser[9, 10]. On the other side, the indirect method for representing the value of reactive power was studied[11]. In [11], the ERC (Equivalent Reactive Compensation) method is defined to evaluate the dynamic reactive source. The value of reactive power of a generator is defined as the equivalent amounts of static condenser required to maintain same voltage level when the designated generator's reactive power set to 0. However, some distortion may be existed in the equivalent amounts because it is defined by the other buses. And it is not sufficient to treat the dynamic sources as static ones since the dynamic sources are more effective for supporting voltage profile. In this study, a direct method for measuring the reactive power used in ancillary service from the relation of a generator and the equivalent system. A definition for measuring the ancillary service terms is given in Section 2 and the validity of the method is demonstrated in Section 3.

2.Contribution analysis of the reactive power of a generator

Reactive power of a generator has been known as independent property with active power. However, the generators cannot ship its active power to the system without proper reactive power support. This means that the reactive power of a generator is used to support the voltage profile of the system and make it possible for shipping its active power to the system. This characteristic is of importance to ancillary service. To ensure the proper level of the voltage, sufficient amounts of reactive power should be supported throughout the system. The main sources of the reactive power in power system are the generators and the transmission system itself. Although the transmission system makes out more reactive power than the total reactive power output of the generators, the generators are essential for supporting the voltage level. In this paper, we assume that the transmission system belongs to the ISO (Independent System Operator) who is obligated to maintain the voltage profile of the total system so that the ISO only consider the cost for the reactive power of the generators.

2.1 Contribution analysis

To figure out the amounts of reactive power used in ancillary service, a model system (Fig. 1) is given. A generator is connected to an infinite system via transmission line. The generator injects $P_g + jQ_g$ to the system and no active power loss is presumed, that is, $Z = jX$. The current is I and the voltage of generator bus is E and the voltage of infinite bus is V.

$$|I|^2 = \frac{P_g^2 + Q_g^2}{|E|^2} \tag{1}$$

From the fact of $P_g = P_{sys}$, the current can be represented in terms of infinite bus.

$$|I|^2 = \frac{P_{sys}^2 + Q_{sys}^2}{|V|^2} = \frac{P_g^2 + Q_{sys}^2}{|V|^2}\ . \tag{2}$$

The reactive power required to support the transmission line is:

$$Q_{req} = |I|^2 X = \frac{P_g^2 + Q_g^2}{|E|^2} X \quad , \text{ or } \quad Q_{req} = |I|^2 X = \frac{P_g^2 + Q_{sys}^2}{|V|^2} X \tag{3, 4}$$

So, the reactive power of the generator is:

$$Q_g = Q_{req} + Q_{sys} = \frac{P_g^2 + Q_{sys}^2}{|V|^2} X + Q_{sys} \tag{5}$$

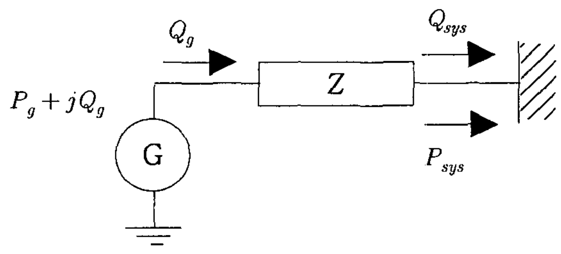

Fig. 1. Relation of a generator and system

In eq.(5), the first term Q_{req} is concerned with the actually transmitted power of the generator to the system, so that this term is the required amount for shipping the power of the generator to the system. On the other hand, the second term Q_{sys} is the supporting amount to the system for balancing the demand and the supply of the reactive power. From eq.(5),

$$Q_g = Q_{req} + Q_{sys} = \left(\frac{P_g^2}{|V|^2}X\right) + \left(\frac{Q_{sys}^2}{|V|^2}X + Q_{sys}\right). \quad (6)$$

Let, $$Q_{g1} = \frac{P_g^2}{|V|^2}X, \quad Q_{g2} = \frac{Q_{sys}^2}{|V|^2}X + Q_{sys}. \quad (7, 8)$$

Since Q_g, P_g, X and V are given value, Q_{g1} is also known by eq.(7). From eq.(6) and Q_{g1}, $Q_{g2}$is acquired and Q_{sys} can be calculated from eq. (8).

$$Q_{sys} = \left(-1 + \sqrt{1 + 4\frac{X}{|V|^2}Q_{g2}}\right) \Big/ \left(2\frac{X}{|V|^2}\right) \quad (9)$$

2.2 Equivalent system

A generator should be represented in the form of Fig. 1. to apply the contribution analysis by the Thevenin Equivalent Theory. Although the load of the power system is not a linear form, it can be transformed into the constant impedance form to be treated in linear system. With the constant impedance load, Thevenin equivalent impedance can be acquired to be Z and the infinite bus voltage V is substituted by Thevenin open circuit voltage (V_{th}) so that the contribution analysis scheme in Section 2.1 can be applied.

3. Case Study

3.1 IEEE New England 39 bus system

New England 39 bus system is adopted to demonstrate the validity of the scheme. It has 10 generators 19 load buses.

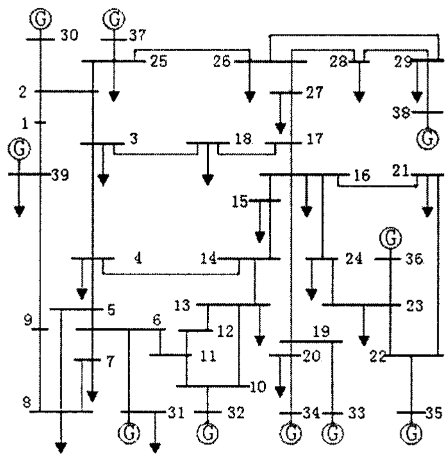

Fig. 2 IEEE New England 39 bus system

Total load is 6097.1MW, 1408.9MVar and total generation is 6144.4MW, 1360.5MVar. We presume the effective output of the generator bus, that is, if the generator and load is located on the same bus, the effective output is the remainder of the generation minus the load of the bus. And if the effective generation is negative, it is set to be 0 (in case of as #39 in Fig. 2).

The output pattern of the generators is given in Table. 1. The power factors of gen. # 30, 31, 35 and 36 are relatively small which means that those generators produce more reactive power than others. The reactive power contribution pattern is given in Table. 2 where, $Q_p = Q_{total} - Q_{sys}$.

Table. 1 Output pattern of generators

Gen. #	MW	Mvar	p.f
30	250	169	0.829
31	524	144	0.964
32	650	148	0.975
33	632	49.4	0.997
34	508	139	0.965
35	650	232	0.942
36	560	198	0.943
37	540	16.2	0.999
38	830	47.7	0.998
39	1000	217	0.977

Table. 2 Reactive power pattern of generators

Gen.	Qtotal	Qp	Qsys
30	169	27.34	141.66
31	144	106.07	37.93
32	148	148.00	0.00
33	49.4	49.40	0.00
34	139	125.58	13.42
35	232	161.09	70.91
36	198	162.80	35.20
37	16.2	16.20	0.00
38	47.7	47.70	0.00
39	217	217.00	0.00

A bar graph for this result is given in Fig. 3. Most part of reactive power of generator #30 is used for supporting the system and some generators such as generator #32, 37, 38, 39 consume all reactive power for shipping its power to system.

From this result, we can say that if a generator is located in the vicinity of the load center, the major part of the reactive power of the generator is used for supporting the system, while the major part of the reactive power is required for shipping its power to the system in case of a remote located generator. This result is due to the eq.(7) which is proportional to X in the vicinity of load center, the equivalent X is relatively small. Therefore, if a generator is located in a remote site from load center, its equivalent impedance X is relatively large so that major part of its reactive power is required for shipping its power to the system.

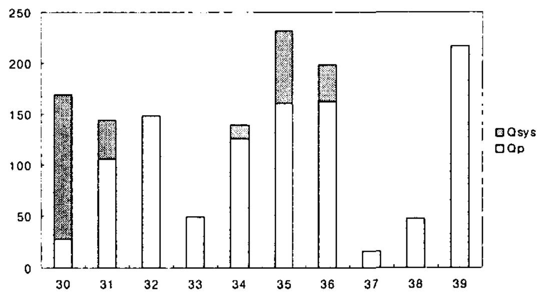

Fig. 3 Reactive power contribution analysis

3.2 Real power system

The proposed scheme is demonstrated by KEPCO (Korea Electric Power Corporation) system whose total load is 50,041MW, 24,348MVar in year 2004. Reactive power contribution patterns are depicted in Fig. 4 for heavy loaded condition and in Fig. 5 for light loaded condition.

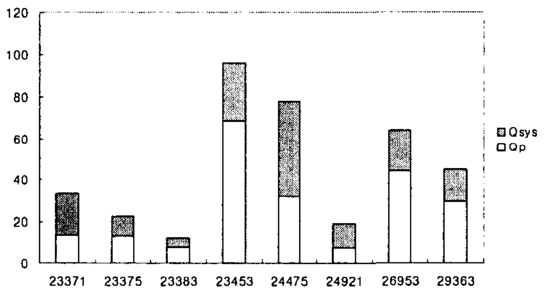

Fig. 4 Reactive power contribution analysis

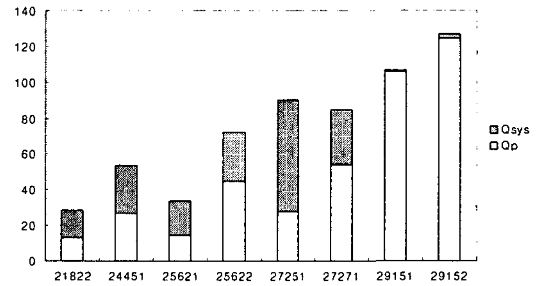

Fig. 5 Reactive power contribution analysis

In the case of heavy loaded condition (Fig. 4), each generator share the burden of supporting the system, while in the case of light loaded condition (Fig. 5), considerable number of generators should turn off so that the voltage profile is not equalized throughout the system. This can cause the long-distance transmission of the power in the light loaded condition. For example, a number of large nuclear generators (such as gen. #29151, 29152 in Fig. 5) are located in southern area remote from the load center located in northern area. Almost all portion of the reactive power of such generators is required for shipping its power to a distant load. And relatively large part of the reactive power of generators located in the vicinity of the load center (such as gen. # 24451, 27251) is used for supporting the reactive power demand of the nearby loads. This phenomenon can be remarkable in light-loaded condition or long-distance power transmission case. Using proposed technique, the ISO can know the reactive power contribution of individual generator to decide the financial compensation for ancillary service.

4. Conclusion

In this paper, an analysis technique is proposed to consider how the reactive power is used for the ancillary service. The proposed formula is based on the Thevenin equivalent system. Several case studies show that a generator located far from loads has large equivalent impedance so that the major portion of the reactive power is required to transmit its power to the load via long distance and relatively small portion is utilized to keep supply and demand of the reactive power in balance. The ISO can utilize this technique to decide the value of the generator in the ancillary service market.

5. References

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