Reactive Power Aspects in Reliability Assessment of Power Systems

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***Abstract*—Reactive power plays a significant role in power system operation. However, in reliability evaluation, attention has seldom been paid to reactive power. In conventional power system reliability evaluations, the fixed maximum and minimum values are applied as the reactive power limits of generators. Failures of reactive power sources are rarely considered. The detailed causes of network violations for a contingency are also seldom studied. Real power load shedding is usually used to alleviate network violations without considering the role of reactive power. There are no corresponding reliability indices defined to represent the reactive power shortage in the existing techniques. Reactive power shortage and the associated voltage violations due to the failures of reactive power sources are considered in this paper. New reliability indices are proposed to represent the effect of reactive power shortage on system reliability. The reliability indices due to reactive power shortages have been defined and are separated with those due to real power shortages. Reactive power limits determined by real power output of a generator using $P-Q$ curve have been studied. A reactive power injection technique is proposed to determine possible reactive power shortage and location. The IEEE 30-bus system has been modified and analyzed to illustrate the proposed technique. The results provide system planners and operators very important information for real and reactive power management.**

***Index Terms*—Contingency screening, load shedding, power system reliability, reactive power, voltage stability.**

I. INTRODUCTION

REACTIVE power is a basic requirement for maintaining system voltage stability. Adequate reactive power reserve is expected to maintain system integrity during post-contingency operation when considering random failures of reactive power resources. As a well-established ancillary service, reactive power support and voltage control plays a vital role in power system operation. The effect of reactive power on system stability and security has been well investigated [1]–[8]. A large area blackout usually occurs in a heavily loaded system which does not have adequate reactive power reserve. The heavily loaded systems usually have high reactive power demand and reactive power loss in transmission network. During a contingency, the real power component of line loading does not change significantly, whereas the reactive power flow can change dramatically [1]. The reason is that bus voltage drop due to a component failure reduces the reactive power generation from the charging of line and shunt capacitors. Therefore, sufficient reactive reserve should be available to meet the Var requirement following a contingency. Reactive power which can be delivered by a power system depends on its network configuration, operating condition, and locations of reactive power sources. The results [1]–[8] show that reactive power is the key to solving system voltage problems in system operation and should be considered in reliability evaluation.

Reliability evaluation techniques have been well developed [9]–[12]. In these techniques, the fixed maximum and minimum values are applied as the reactive power limits of generators. Network violations in a contingency state are usually alleviated through real power load shedding with less consideration for the role of reactive power. The post-contingency voltages, reactive power generation, and power flows were estimated using sensitivity analysis [13]. Through employing piecewise linear estimation, the effect of equipment limits on the estimates was captured. The effect of a shunt capacitor on distribution system reliability was studied [14]. The effect of voltage limits and reactive power constraints on system reliability was investigated using dc power flow technique [15]. The expected value of the curtailed kWh due to the lack of reactive power generation and the expected value of voltage irregularity were calculated [15].

However, the following problems were seldom considered in the existing reliability techniques. First, most existing techniques ignored failures of reactive power resources such as synchronous condensers and Var compensators. Second, network violations due to real power shortage have not been differentiated from those due to insufficient reactive power during post-contingency load shedding. Third, there are no indices and the corresponding technique to solve reliability problems related to reactive power inadequacy. Finally, the correlation between real and reactive power output from a generator, which is determined by $P-Q$ curve, has not been considered. Therefore, the existing reliability indices are not sufficient for system planners and operators to make reasonable planning and operation decisions.

This paper proposes a technique to evaluate reliability indices which take into account both real and reactive power shortage due to failures caused by real and reactive power sources such as generators, synchronous condensers, and compensators. Reactive power shortage and its associated voltage violations due to failures of reactive power sources are considered. New reliability indices are proposed to represent the effect of reactive power shortage on system reliability. The reliability indices due to reactive power shortages are separated with those due to real

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power shortages. A reactive power injection technique is proposed to determine reactive power shortage and location. Reactive power limit of a generator determined based on its real power output have been studied using $P-Q$ curve.

Section II briefly reviews the reactive power issues related to power system reliability. The voltage set point for load shedding is also discussed. In Section III, the basic reliability model for a component including reactive power source is introduced. Reliability indices related to real and reactive power are defined. The contingency filtering technique for reliability evaluation is also discussed. The reliability evaluation technique is proposed in Section IV. The load shedding and reactive power injection methods including both real and reactive power shortages are also introduced. The modified IEEE 30-bus system has been analyzed using the proposed techniques and the results are presented in Section V. Section VI concludes the paper.

II. REACTIVE POWER ISSUES

A. Reactive Power Characteristics

There are three aspects that differentiate reactive power from active power in power system operation and should be considered in reliability evaluation. First, it is not efficient to transfer reactive power over a long distance because reactive power losses in transmission lines are significant and bus voltage is very sensitive to reactive power. Therefore, reactive power shortage is usually compensated locally in weakly connected grids. Second, the major role of reactive power is to maintain voltage stability/security of power systems. Therefore, the effect of reactive power on system reliability in terms of energy not supplied is indirect and should be calculated based on reactive power shortage and voltage violations. Finally, the reactive power losses change with system configuration and operation conditions [7], [8]. Reactive power requirements for voltage restoration after a contingency are heavily dependent on reactive power reserve distributions in a power system. In order to reasonably determine the real and reactive power dispatch and post-contingency load shedding, the characteristics of real and reactive power corresponding to bus voltage and their correlation have to be considered. The characteristics of real and reactive power have been comprehensively studied [16]–[18]. The $P-V$, $Q-V$, and $P-Q$ curves which show the coupling among active power, reactive power, and voltage are considered in real and reactive power dispatch and load shedding in this paper.

B. Under-Voltage Control and Load Shedding

Bus voltage stability is a very important issue in power system operation and should be considered in reliability evaluation. There are the existing techniques to solve voltage stability problems caused by reactive power shortage. In general, preventive or corrective control can mitigate the voltage problems. The preventive control aims to prevent voltage instability before it actually occurs, whereas the corrective control is to stabilize a post-contingency severe system through actions such as compensation reactors switching, generator voltage pick-point increasing, secondary voltage control and generation re-dispatch, etc. Under-voltage load shedding is the last resort to solve severe voltage problems and is used in this paper to determine the load curtailments caused by reactive power shortage [19]–[21]. The 10% post-voltage deviation below the lowest normal voltage (95%) is accepted when considering up to the second order contingencies based on [22]–[24]. Both 0.85 pu and 0.9 pu are used as the voltage set points for load shedding in this paper.

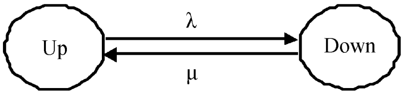

Fig. 1. Two-state model of a component.

III. RELIABILITY INDICES AND CONTINGENCY SCREENING

A. Component Reliability Model

A system component such as a generator, a transmission line, or a reactive power compensator can be represented using the two-state reliability model [25] as shown in Fig. 1. The availability A and unavailability U of a component can be calculated based on its failure rate λ and repair rate μ using the following equations:

$$A = \frac{\mu}{\lambda + \mu} \tag{1}$$

$$U = \frac{\lambda}{\lambda + \mu}. \tag{2}$$

B. System Reliability Parameters

For a power system with N independent components, the state probability p_i, the departure rate λ_i, the frequency F_i, and the total system available real power capacity P_i for state i with M failed components can be determined using the following equations:

$$p_i = \prod_{j=M+1}^{N} A_j \prod_{j=1}^{M} U_j \tag{3}$$

$$\lambda_i = \sum_{j=M+1}^{N} \lambda_j + \sum_{j=1}^{M} \mu_j \tag{4}$$

$$F_i = p_i \lambda_i \tag{5}$$

$$P_i = \sum_{k=1}^{Ngi} P_k \tag{6}$$

where A_j, U_j, λ_j, and μ_j are the availability, the unavailability, the failure rate, the repair rate of component j, respectively, P_k is the real power capacity of generator k, and Ngi is the number of available generators in the system for state i. It should be noted that the state probability have to be adjusted for a common cause failure.

C. Reliability Indices

In order to provide reliability information on both system real and reactive power for system planners and operators, the expected real and reactive power load curtailments due to real power shortages are defined as ELC_P and EQC_P, respectively. The expected real and reactive power load curtailments due to reactive power shortage or voltage violations are defined as ELC_Q and EQC_Q, respectively. The expected energy not supplied due to the real power and reactive power shortages are represented by $EENS_P$ and $EENS_Q$, respectively. The