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.

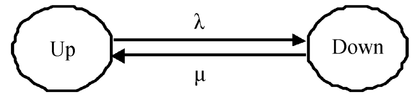

Fig. 1. Two-state model of a component.

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 expected Var not supplied due to real and reactive power shortages are represented by $EVNS_P$ and $EVNS_Q$, respectively. The expected Var shortage due to voltage violation is defined as $EVarS$. Those indices can be defined using the following equations:

$$ELC_P = \sum_{i=1}^{NC} LC_{Pi} \times F_i \tag{7}$$

$$ELC_Q = \sum_{i=1}^{NC} LC_{Qi} \times F_i \tag{8}$$

$$EQC_P = \sum_{i=1}^{NC} QC_{Pi} \times F_i \tag{9}$$

$$EQC_Q = \sum_{i=1}^{NC} QC_{Qi} \times F_i \tag{10}$$

$$EENS_P = \sum_{i=1}^{NC} LC_{Pi} \times p_i \times 8760 \tag{11}$$

$$EENS_Q = \sum_{i=1}^{NC} LC_{Qi} \times p_i \times 8760 \tag{12}$$

$$EVNS_P = \sum_{i=1}^{NC} QC_{Pi} \times p_i \times 8760 \tag{13}$$

$$EVNS_Q = \sum_{i=1}^{NC} QC_{Qi} \times p_i \times 8760 \tag{14}$$

$$EVarS = \sum_{i=1}^{NC} VarS_{Qi} \times p_i \times 8760 \tag{15}$$

where NC is the total number of considered contingencies, LC_{Pi} and QC_{Pi} are the real and reactive load curtailments due to real power shortage for state i respectively, LC_{Qi} and QC_{Qi} are the real and reactive load curtailments due to reactive power shortage for state i respectively, and $VarS_{Qi}$ is the Var shortage which causes voltage violation for state i.

The expected Var shortage at each bus can be used to select the optimal location for the installation of additional reactive power compensators in system planning and operation.

D. Contingency Screening and Filtering

The number of system operating states for a practical large power system will explode tremendously when considering up to the second-order failures and hourly load duration curve for a year. Therefore, contingency filtering or screening should be used to reduce the number of considered states based on the specific accuracy. Most existing contingency selection techniques in reliability evaluation are based on the probabilities of contingency states. The contingencies with the larger probabilities than a given value will be considered and determined using the state selection technique [26]. In security analysis, different techniques [27], [28] have been proposed to reduce the computing time for real-time screening.

Considering the special requirement of reliability evaluation, a contingency filtering index is defined in this paper based on the combination of the state probability and the performance index which is similar to the ones used in [27] to select the contingency states. There are two types of system states: the states with the isolated buses due to line failures and the states without the isolated buses. For the states without the isolated buses, the proposed filtering index is the multiplication of the state probability and the severity index. Severity index for different contingency is defined as follows,

For a contingency with two failed generators, the severity index is the ratio of the total real power capacity of the failed generators to the total system real power load for the normal state.

For a contingency with two failed lines, the severity index is the ratio of the total real power flow of the failed lines to the total system real power load for the normal state.

For a contingency with one failed line and one failed generator, the index is the ratio of the real power flow of the failed line plus the real power capacity of the failed generator to the total system real power load for the normal state.

All the states up to second-order failures with the isolated buses should be considered because of the complete cutoff of the loads at those buses.

IV. Reliability Evaluation Technique

A. Real and Reactive Power Load Shedding

A two-stage load shedding process is proposed in order to distinguish the reliability indices due to reactive power shortage from those caused by the real power shortage. The objective is to provide detailed information to system planners and operators regarding current and future PQ resources.

Stage 1) The total available system real power capacity P_i including both generation and reserve is compared with the total system real power demand P_{di} including the total real power load and transmission loss. The ac power flow is performed to calculate transmission loss for contingency state i. If P_i is less than P_{di}, real power loads at all the load buses are curtailed in system range using the proportional or other load shedding techniques. Reactive power load at each bus is also curtailed correspondingly based on the initial power factor. The proportional method is a commonly used load shedding technique in reliability evaluations and is used in this stage. In this technique, the total P shortage, which is $P_{di} - P_i$, is shared by all the load buses based on their percentages in total system load. The loads at all buses are curtailed simultaneously based on the percentages.

Stage 2) After the first stage load shedding, perform ac power flow analysis. Check Q injections at all PV buses and voltage violations at other buses. If Q injection at a PV bus reaches its maximum limit, change it into PQ bus to fix their reactive power injection. Q injection will change during the load shedding. If the voltage at some of the load buses is below the voltage set point, the problems are related to the local reactive power shortage. The load shedding is required to solve the Q shortage problems. Because of the low efficiency of delivering reactive power through a long distance, the load shedding is usually performed at the nodes with the voltage violations. Both the real and reactive power loads are curtailed iteratively in step of 1% with the fixed power factor until the voltage violation is eliminated. The reason behind selecting a small step of 1% of the reactive load during the iterative load shedding process is that the voltage is very sensitive to reactive power load. If the step is larger, the low voltage limit cannot be smoothly reached in the iteration process. If the voltage violation at those buses still exists after the loads are completely curtailed, it is necessary to cut the loads at their adjacent nodes according to the local characteristics of reactive power. It should be noted that voltage stability depends heavily on active load distribution in the system. For complex networks, the concepts of electrical distance and voltage control areas/zones should be considered to identify the adjacent nodes for load shedding. More techniques for load shedding and reactive compensation [21], [29]–[31] can be used for mitigating the voltage problems. The objective of this stage is to provide information to system planners and operators regarding local Q shortage.

It should also be noted that load shedding is the last resort to solve the voltage problem. The voltage set point as discussed in Section II is very important for the under voltage load shedding. For the states with the isolated buses, the loads of those buses cannot be supplied.

B. Reactive Power Injection

The voltage violations related to Var shortage can also be solved by additional local Q injection or compensation. In this method, reactive power is injected at the nodes with the voltage violations to restore the voltage. When the voltage reaches the voltage set point, the corresponding reactive power injected is the Q shortage $VarS_Q$. It should be noted that the effect of reactive power injection on bus voltage is very sensitive to network configuration and reactive power source distribution. In this paper, the reactive power is gradually injected in step of 1% of the reactive load at a bus with the voltage violation until the voltage problem solved. The objective of reactive power injection is to provide additional information for system operators and planners to add new reactive power sources in future planning and operation.

C. Procedure of Reliability Evaluation

The procedure of the proposed technique includes the following steps.

- Step 1) Input network and component data such as reliability and network parameters.
- Step 2) Determine the system states using the proposed state filtering technique.
- Step 3) Calculate basis system reliability parameters for state i.
- Step 4) Calculate the total system available real power capacity P_i and the total demand P_{di} using ac power flow.
- Step 5) Compare P_i with P_{di}. If P_i is larger than P_{di}, go to the next step. Otherwise, cut real and reactive load proportionally at all the load buses until P_i and P_{di} are balanced. Update ELC_P, EQC_P, $EENS_P$, and $EVNS_P$.
- Step 6) Perform ac power flow analysis and check Q injections at all PV buses. If the Q injection at a PV bus is at its maximum limit, change it into PQ bus.
- Step 7) Determine the voltage violation. Go to Step 8 to determine the reactive power shortage $VarS_{Qi}$ if there is the voltage violation. Otherwise, go to Step 13.
- Step 8) Release the voltage violation using the Q injection method (Step 8 and Step 9): Inject the reactive power 1% at the nodes with the voltage violation using the method discussed in Section IV-B and update $VarS_{Qi}$.
- Step 9) Check the voltage violations using ac power flow analysis. If the voltage violations still exist, go to Step 8. Otherwise, update the total $EVar_S$.
- Step 10) Remove the accumulative reactive power injected to the buses at Step 8 and go to Step 11 to determine the load curtailment due to the voltage violation.
- Step 11) Release the voltage violation using the local load curtailment method (Step 11 and Step 12): Cut the real and reactive power load 1% at the buses with the voltage violations determined in Step 7 using the method presented in Section IV-A and update QC_{Qi}.
- Step 12) Check the voltage violations using ac power flow analysis. If the voltage violations still exist, go to Step 11. Otherwise, update the total $EVNS_Q$ and go to the next step.
- Step 13) If all the specific contingencies are considered, go to the next step. Otherwise, go to Step 3 for the next state.
- Step 14) Calculate the system reliability indices.

The $P-Q$ curve is used to determine the Q limit if the correlation between P and Q is considered in reliability analysis.

It should be noted that the over-voltage problems should be checked when the reactive power at a PV buses reach its limit. It should be also noted that the selection from the two methods used to release the voltage violations depends on the comparison between the cost for installing the new compensators and the customer interruption cost due to the load curtailment. If the cost of the former is less than the cost of the latter, the new capacitors should be installed in the network.

V. System Studies

The modified IEEE 30-bus system [32] as shown in Fig. 2 was analyzed to illustrate the proposed technique. The system was selected due to the high requirement of reactive power compensation caused by the special configuration from the two generation stations to the remote loads. The system has five PV buses and 24 PQ buses. The total system active and reactive power peak loads for the normal state are 283.4 MW and 126.2 MVar, respectively. It is assumed that 4×60 MW units are connected at Bus 1 and 3×40 MW units at Bus 2 in order to consider generator reliability in the evaluation. The reliability parameters for generators and transmission lines [33] are used in this paper and are shown in Tables V and VI. The effects of the different aspects of reactive power on system and load point reliability are studied and presented in this section.

A. Basic Reliability Analysis

The fixed reactive power limits shown in Table V for the generators and condensers are used in the analysis. Annual constant peak load is used in this case. The real and reactive power load at each bus is bundled together using the fixed initial power factor [32] during load shedding. The states up to second order failures have been considered. The load point and system $EENS_P$,

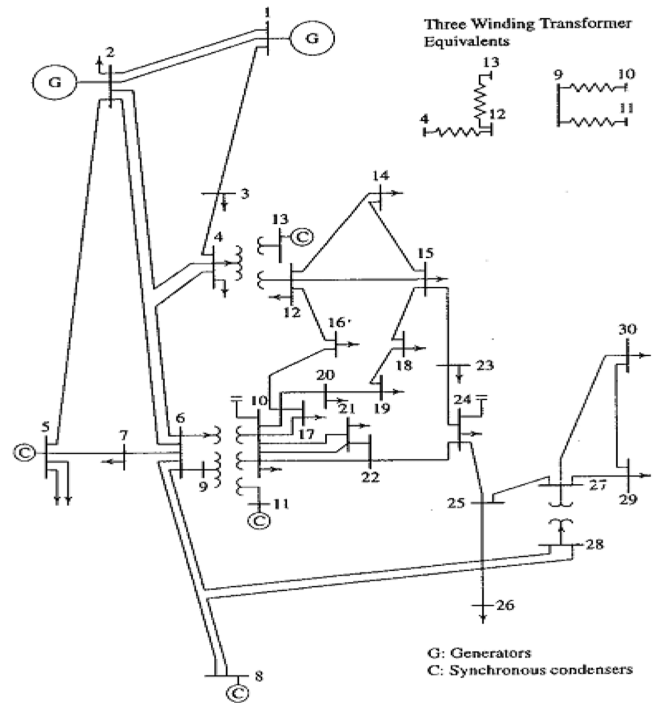

Fig. 2. Single line diagram of IEEE 30-bus system.

TABLE I
LOAD POINT AND SYSTEM $EENS_P$, $EENS_Q$, ELC_P, AND ELC_Q

Bus	$EENS_P$ (MWh/yr)	$EENS_Q$ (MWh/yr)	ELC_P (MW/yr)	ELC_Q (MW/yr)
2	274.73	0	17.0566	0
3	30.40	0	1.8904	0
4	96.22	0	5.9738	0
5	1194.05	12.3818	74.3545	1.7146
7	289.01	0.9068	17.9966	0.1256
8	380.39	1.2640	23.7046	0.1806
10	73.43	0	4.5589	0
12	141.80	0.7405	8.8034	0.1046
14	78.60	0.3305	4.8964	0.0467
15	103.82	0	6.4454	0
16	44.57	0	2.8074	0
17	114.46	0.2465	7.1855	0.0533
18	40.68	0	2.5510	0
19	120.93	0.0811	7.6084	0.0176
20	27.93	0.0011	1.7456	0.0002
21	224.89	1.0330	14.4755	0.2230
23	40.70	0.0884	2.5548	0.0191
24	110.15	0.0741	6.8384	0.0161
26	208.51	4.9766	23.8002	0.7218
29	31.48	28.1530	2.1226	3.6058
30	139.03	17.1324	9.3747	2.2980
System	3765.77	67.4098	246.7447	9.1271

$EENS_Q$, ELC_P, and ELC_Q are shown in Table I when the voltage set point is assumed to be 0.9 pu.

It can be seen from Table I that the load point at Bus 5 has the highest $EENS_P$ followed by the load point at Bus 8 and Bus 7. The higher $EENS_P$ at these buses are due to the higher load level compared with other load points. Unlike $EENS_P$, the load point at Bus 29 has the highest $EENS_Q$ followed by the load point at Bus 30. The reason is that there is no local reactive power compensator at the nearest surrounding buses and the transmission lines from the other compensators to the two buses are very long. The results also show that the system $EENS_Q$ is about 1.8% of the $EENS_P$. 47.21% of the total $EENS$ at Bus 29 is due to the reactive power shortage. This indicates that the reactive power compensation for some load point is critical for post contingency restoration. The system $EENS_Q$ caused by the reactive generation limit and voltage violation is 1.76% of the total $EENS$.

TABLE II
LOAD POINT AND SYSTEM $EVNS_P$, $EVNS_Q$, EQC_P, AND EQC_Q

Bus	$EVNS_P$ (MVarh/yr)	$EVNS_Q$ (MVarh/yr)	EQC_P (MVar/yr)	EQC_Q (MVar/yr)
2	160.79	0	9.9824	0
3	15.20	0	0.9452	0
4	20.26	0	1.2576	0
5	240.84	2.4974	14.9972	0.3458
7	138.17	0.4335	8.6037	0.0600
8	380.39	1.2640	23.7046	0.1806
10	25.32	0	1.5720	0
12	94.95	0.4958	5.8915	0.0701
14	20.28	0.0853	1.2636	0.0120
15	31.65	0	1.9651	0
16	22.92	0	1.4438	0
17	73.76	0.1588	4.6307	0.0344
18	11.44	0	0.7175	0
19	43.28	0.0290	2.7230	0.0063
20	8.89	0.0004	0.5554	0
21	143.92	0.6611	9.2643	0.1427
23	20.35	0.0442	1.2774	0.0096
24	84.83	0.0571	5.2663	0.0124
26	137.02	3.2703	15.6401	0.4743
29	11.80	10.5574	0.7960	1.3522
30	24.92	3.0709	1.6804	0.4119
System	1710.99	22.6253	114.1814	3.1124

Table II shows the load point and system $EVNS_P$, $EVNS_Q$, EQC_P, and EQC_Q. The system expected Var curtailment due to the reactive power shortage is smaller than that due to the real power shortage. The reason is that the reactive power load has been curtailed in the first stage load shedding. In a practical power system, real and reactive power should be curtailed based on the characteristics of loads.

B. Load Curtailment and Var Compensation

Most existing reliability evaluation techniques alleviate voltage violations through real and reactive power load shedding (method 1). The reactive power injection (method 2) is also studied in this paper to solve the same problem. The objective of load shedding or Var injection is to restore voltage at each bus to its low limit. Table III shows total load point and system $EENS$ obtained using the two methods. The corresponding real and reactive load curtailments for method 1 and Var compensation for method 2 due to voltage violations are also provided in Table III.

If the reactive power is injected at the corresponding buses to eliminate the voltage violation, the total system $EENS$ will be reduced by about 2% compared with those from the load shedding method. The total expected reactive power injection is 68.039 MVarh/yr. The highest reactive power injection is at Bus 29 followed by Bus 30 and Bus 5. The results provide information to system planners for future allocation of reactive power compensators.

TABLE III
RELIABILITY INDICES FOR TWO METHODS

Bus	*EENS* (MWh/yr) Method 1	*EENS* (MWh/yr) Method 2	*EVarS* (MVarh)/yr Method 2	*ELC* (MW/yr) Method 2	*EQC* (MVar/yr) Method 2
2	274.73	274.79	0	0	0
3	30.40	30.41	0	0	0
4	96.22	96.24	0	0	0
5	1206.44	1194.30	10.0120	1.7146	0.3458
7	289.91	289.07	1.2564	0.1256	0.0600
8	381.65	380.47	1.4203	0.1652	0.1652
10	73.43	73.45	0	0	0
12	142.54	141.83	0.8645	0.1046	0.0700
14	78.93	78.62	0.2732	0.0467	0.0120
15	103.82	103.84	0	0	0
16	44.57	44.58	0	0	0
17	114.71	114.48	0.3228	0.0533	0.0343
18	40.68	40.69	0	0	0
19	121.01	120.95	0.0762	0.0176	0.0063
20	27.93	27.93	0.0021	2.4370	7.7543
21	225.93	224.94	1.2594	0.2230	0.1427
23	40.78	40.71	0.0799	0.0191	0.0096
24	110.22	110.17	0.1040	0.0161	0.0124
25	0	0	1.8098	0	0
26	213.49	208.52	4.4569	0.7218	0.4743
27	0	0	8.6035	0	0
29	59.63	31.48	23.1530	3.6058	1.3522
30	156.16	139.06	14.3450	2.2980	0.4119
System	3833.18	3766.53	68.0390	11.5484	10.8510

C. Effect of Voltage Set Point

The effect of the voltage set point on reliability indices is also studied. The reliability indices for the voltage set point 0.85 pu are also calculated. The system $EENS_Q$ for the voltage set point 0.85 pu is significantly reduced to 9.4078 MWh/yr from 67.4098 MWh/yr for the voltage set point 0.9 pu. The system $EVarS$ for the voltage set point 0.85 pu is significantly reduced to 8.72 from 68.0390 MVar/yr for the voltage set point 0.9 pu. The results indicate that less load will be curtailed and less Var injection is required if the system can be maintained in stable operation at the low voltage of 0.85 pu. It should be noted that the reliability margin for a post-contingency will also be reduced due to the lower voltage set point.

D. Effect of Load Variation

In order to consider the effect of real and reactive power on reliability under different load conditions, the reliability indices based on load duration curve has to be calculated. Hourly load duration curve is determined based on the annual peak load and the hourly, daily, and monthly percentages [33]. The load duration curve [33] is approximately represented using 14 load levels in step of 5% difference from the highest to the lowest load level. The reliability indices for the different load levels using two different methods are displayed in Fig. 3. The total system $EENS$ decreases when the load level reduces from 100% to 80% of the peak level for the two methods. There is very small difference between the results from the two methods. When load levels are less than or equal to 80% peak load, the system $EENS$ for method 1 and method 2 are the same because there are no network violations for most of the contingency states except the states with the isolated buses. The total annual reliability indices

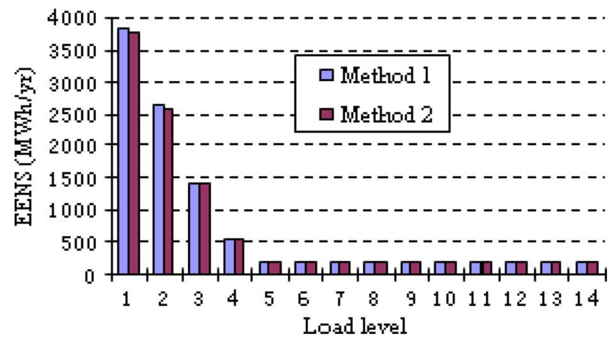

Fig. 3. System $EENS$ from load duration curve.

TABLE IV
SYSTEM RELIABILITY INDICES FOR TWO METHODS

EENS (MWh/yr) Method 1	*EENS* (MWh/yr) Method 2	*EVarS* (MVarh)/yr Method 1	*ELC* (MW/yr) Method 2	*EQC* (MVar/yr) Method 2
154.27	152.15	1.96	0.2893	0.0864

are shown in Table IV. The total annual system $EENS$ and $EVarS$ are significantly reduced compared with those using constant annual peak load. Therefore, results from the annual constant peak load give a pessimistic estimation. More accurate results can be obtained using the hourly load duration curve.

E. Effect of $P-Q$ Correlation of Generator

In conventional power system reliability evaluation, the maximum reactive power provided by a generator is assumed to be constant. However, the maximum reactive power provided by a generator is closely related to its real power output. When the real power output from a generator is determined for a contingency state, the corresponding reactive power output is determined by the $P-Q$ curve. More reactive power can be provided when the real power output is low. The effect of the real power output of a generator on its reactive power limit is studied in this section.

The generators at Bus 1 are used to illustrate the effect of $P-Q$ curve of the generators. All the other PV buses are changed to PQ buses with the fixed Q limits shown in Table VII. Only the second order failures of a single generator at Bus 1 and a single line in the system are studied to illustrate the effect.

The results obtained using the $P-Q$ curves of the generators (Case 1) are compared with those from the constant reactive power limits (Case 2). The results of $EENS_Q$ for the two cases are shown in Fig. 4. The $EENS_Q$ for Case 2 is about 1.5 times that of Case 1, which means that more reactive power can be supplied by the generators at Bus 1 for Case 1 than that for Case 2. Therefore, the reactive power capability of the generators is not fully utilized under the fixed reactive power limit in Case 2. The maximum reactive power Q which can be provided by the generators under different system load levels is underestimated in this system. Although the reactive power generation limit can be determined using $P-Q$ curve based on the real power output, the chance of a generator operating at its limit is very small. There are only eight such cases out of 40 contingencies.

It can be concluded from the analysis that the real and reactive power capability of a generator is utilized to its most extent, and the load curtailment is the least when the reactive power limits

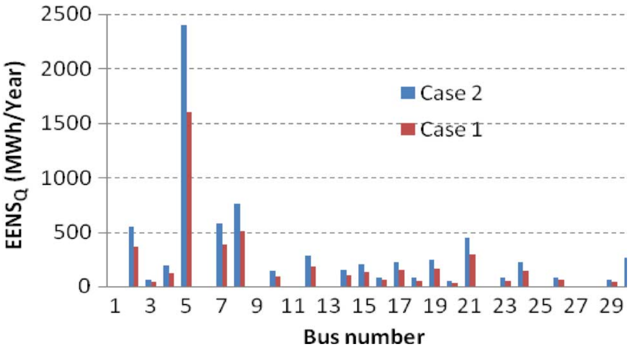

Fig. 4. $EENS_Q$ of the load points.

TABLE V
RELIABILITY PARAMETERS AND REACTIVE POWER LIMITS

	Bus	Q_{min}	Q_{max}	λ	μ
Generator	1	-20	25	6	194.67
	2	-20	20	4.5	219
Compensator	5	-20	25	6	194.67
	8	-10	25	6	194.67
	11	-6	20	6	194.67
	13	-6	20	6	194.67

are determined using the $P-Q$ curve based on the real power output.

F. Effect of Contingency Screening

The proposed contingency screening or filtering technique is used to reduce the number of states. In this technique, ac power flow technique is performed to determine power flow of lines. The proposed filtering index is determined based on the state probability, generator capacity, line capacity, and total system load using the method presented in Section III-D. The total $EENSs$ for the contingency states are arranged from the largest to the smallest in descending order using the proposed technique. All the selected states using the technique are the most severe states if the fixed number of the states is used for state selection. The total $EENSs$ for the different number of states are also compared with those obtained from all the second order contingencies. The results show that the difference is only 3.8% when the first 51 out of 1378 up to second-order states are considered. Therefore, the proposed contingency filtering technique can significantly reduce the number of states to be analyzed within acceptable accuracy. It should be noted that the contingency filtering technique required may change with network configurations and generator locations and should be carefully studied in a practical system.

VI. CONCLUSIONS

This paper investigates reactive power aspects in power system reliability evaluation. A technique is proposed to evaluate system and load point reliability of power systems with reactive power shortage due to failures caused by reactive power sources such as generators, synchronous condensers, and compensators. The reliability indices due to reactive power shortage are separated with those due to real power shortage.

TABLE VI
RELIABILITY PARAMETERS OF TRANSMISSION LINES

From Bus	To Bus	λ	μ
1	2	1	876
1	3	1	876
2	4	1	876
3	4	1	876
2	5	1	876
2	6	1	876
4	6	1	876
5	7	1	876
6	7	1	876
6	8	1	876
6	9	1	876
6	10	1	876
9	11	1	876
9	10	1	876
4	12	1	876
12	13	1	876
12	14	1.5	876
12	15	1.5	876
12	16	1.5	876
14	15	1.5	876
16	17	1.5	876
15	18	1.5	876
18	19	1.5	876
19	20	1.5	876
10	20	1.5	876
10	17	5	876
10	21	5	876
10	22	5	876
21	22	5	876
15	23	5	876
22	24	1.5	876
23	24	1.5	876
24	25	1.5	876
25	26	5	876
25	27	5	876
28	27	1.5	876
27	29	5	876
27	30	5	876
29	30	5	876
8	28	1.5	876
6	28	1	876

Reactive shortage is determined using reactive power injection at the nodes with the voltage violation to provide more information for system planning and operation. The effect of $P-Q$ curve on system reliability has been studied. The IEEE 30-bus test system is modified and analyzed to illustrate the technique and models. The results show that reactive power will have significant impact on system reliability and should be considered in reliability evaluation. The proposed new reliability indices provide very important information for system planners and operators to make their decisions. The paper also provides different ways for system operators to alleviate network violations and to find the optimal location for installing new reactive power compensators.

APPENDIX

Table V lists the reliability parameters and reactive power limits, Table VI lists the reliability parameters of transmission

TABLE VII
INJECTED Q AFTER CONVERTING PV BUSES INTO PQ BUSES

Bus	5	8	10	11	13	24
Injected Q (*MVar*)	12	12	10	10	10	2

lines, and Table VII lists the injected Q after converting PV buses into PQ buses.

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