Reliability Improvement Considering Reactive Power Aspects in a Smart Grid with Demand Side Management

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***Abstract*—Reactive power plays a prime role in power system operation.But contingencies due to reactive power shortages are rarely considered while evaluating the reliability of a system.This paper takes into account the failure of reactive power sources also while evaluating reliability of a system and calculates a separate set of reliability indices due to reactive power shortage.Demand Side Management (DSM)is a promising attempt in improving the system reliability.Here we consider the novel concept of including the effect of reactive power failures in DSM reliability studies.Reliability indices are evaluated for the modified IEEE 30 bus system and also for the same one where DSM is already in operation,which makes it a smart grid. We see that the reliability is improved in the latter case even on considering reactive power source failures also.**

I. Introduction

The role of reactive power in power system operation is increasing day by day with the increase in electrical demand. It is the basic requirement for maintaining voltage stability and hence for voltage control.Reactive power support is also a well established ancillary service.In [1]–[3] , the effect of reactive power on system security and stability was studied. Heavily loaded systems generally have high reactive power demand and high reactive power losses and any contingencies on the same may not change real power loading significantly,but the reactive power flow can vary tremendously.Therefore,sufficient reactive power reserves are to be maintained to meet the reactive power requirements following a contingency.Reactive power available at any point in the system depends on its network configuration,location of reactive power reserves and on its operating condition.From [1]–[3], it is clear that reactive power is utmost important for proper operation of power system and hence should be considered in reliability evaluation.

Reliability evaluation techniques have been well developed [4]–[6]. The reactive power generation,post-contingency voltages,and power flows were estimated in [7] using sensitivity analysis.In [8],the effect of shunt capacitor on distribution system reliability was investigated.In [9],DC power flow was used to study the effect of voltage limits and reactive power constraints on system reliability.But in most of the literature,reactive power source failures were not considered while evaluating system reliability.In [10] this has been taken into account and the authors have proposed a technique to evaluate separate reliability indices considering the failures of both real and reactive power sources such as generators, compensators and condensers.A set of new indices were proposed by them to account for reactive power shortage on system reliability.In this paper,we have used the same technique to account for the failure of reactive power sources while calculating reliability.

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In the era of Smart Grid,Demand Side Management plays a key role.DSM aims at reducing peak demand, reducing generation cost, reducing pollutant emission levels,etc by altering electricity consumption patterns, thus increasing the stability and reliability of the smart grid. In [11] a DSM strategy had been formulated based on load shifting to reduce electricity bill.In [12]–[15] ,the effect of DSM and demand response on improving system reliability were studied.But the effect of DSM on reliability when considering failure of reactive power sources were not evaluated.

II. Problem Definition

In this paper, we take the modified IEEE 30 bus system and calculate reliability indices taking into account the failures of real and reactive power sources as in [10].We then consider the system to be a smart grid where day ahead DSM is actively in operation.The DSM was formulated as in [11].Then we calculate reliability indices for this system considering the failures of both real and reactive power sources. On comparison, we see that in a system with DSM, system reliability is improved even in the case of reactive power source failures also.

III. Reliability Indices and Reliability Evaluation

A. Component Reliability Model

Two state reliability model as shown in Fig. 1, is considered here to represent any system component such as a generator,transmission line or a reactive power compensator

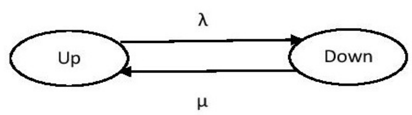

Fig. 1. Reliability Model

[16]. The following equations gives the availability A and unavailability U of the components,calculated using failure rate λ and repair rate μ.

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

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

B. System Reliability Parameters

For a power system with N independent components, for the state i with M failed components ,the state probability p_i , the frequency F_i, total real power capacity P_i can be found out as

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

$$F_i = p_i \lambda_i \tag{4}$$

$$P_i = \sum_{k=1}^{N_{gi}} P_k \tag{5}$$

where P_k is the real power capacity of generator k and N_{gi} is the number of available generators in the system for state i.

C. Reliability Indices

As in [10],the expected energy not served due to real and reactive power shortages are defined as $EENS_P$ and $EENS_Q$ respectively.The expected VAr not supplied due to real and reactive power shortages are denoted as $EVNS_P$ and $EVNSQ$ respectively. These indices are defined in the following equations :

$$EENS_P = \sum_{i=1}^{NC} LC_{Pi} \times p_i \times 8760 \tag{6}$$

$$EENS_Q = \sum_{i=1}^{NC} LC_{Qi} \times p_i \times 8760 \tag{7}$$

$$EVNS_P = \sum_{i=1}^{NC} QC_{Pi} \times p_i \times 8760 \tag{8}$$

$$EVNS_Q = \sum_{i=1}^{NC} QC_{Qi} \times p_i \times 8760 \tag{9}$$

where NC is the total number of contingencies considered,LC_{Pi} and QC_{Pi} are the real and reactive power load curtailments due to real power shortages for the state i respectively,LC_{Qi} and QC_{Qi} are the real and reactive power load curtailments due to reactive power shortages for the state i respectively.

IV. Smart Grid and Demand Side Management

Smart Grid is the future era of power systems.The basic features of Smart Grid includes bidirectional power flow,increased customer participation,hack-proof self healing,improved power quality,electricity market based efficient operation [17].Effective communication technologies are the key to the smart grid. DSM is an important aspect of the smart grid. The DSM controller communicates the prices to the customers and obtains an optimal schedule based on customer preferences and the electricity prices.

The day ahead DSM strategy used in this paper is explained in this section. Load shifting is performed to achieve a variety of objectives like reduction in electricity bill,generation cost,flatenning the load profile,minimizing peak demand etc.Differential Evolution (DE) has been used for this optimization.DSM implementation is possible only by taking the advantage of smart grid communication system.The effectiveness of this scheduling depends of number of available shiftable devices and the maximum delay allowed for each device.Customer can prioritize the devices and set aside the critical ones as non schedulable devices.The users can also set the maximum delay for each device.

V. DSM Formulation

In this DSM strategy ,the time instant at which the devices are connected/disconnected are varied to get the load curve as close to objective load curve as possible. This is modeled as :

$$minimize \quad \sum_{t=1}^{24} (P_{load}(t) - P_{objective}(t))^2 \tag{10}$$

where, $P_{load}(t)$ is the scheduled consumption of all devices at time interval t, $P_{objective}(t)$ is the consumption of all devices in an ideal case,the objective being decided by the DSM controller.The study period has been taken as 24 hours long.

$P_{load}(t)$ is given as:

$$P_{load}(t) = Forecast(t) + Connect(t) - Disconnect(t) \tag{11}$$

It can be safely assumed that the cost of generation does not go to zero at any hour that will make the fraction an infinity.

where, $Forecast(t)$ is the predicted load consumption at time t of the day, $Connect(t)$ is the total rating of all the schedulable appliances which were shifted from any other time interval of the day to time t, while $Disconnect(t)$ is the total rating of all the schedulable appliances which were shifted from the time interval t to another time interval of the day. $P_{objective}(t)$ is modeled as a function which is inversely proportional to the forecasted electricity price of the grid at that hour. This is given by the following equation:

$$P_{objective}(t) = \frac{C_m}{C(t)} \times unshedulable(t) \tag{12}$$

where, C_m is the mean of forecasted costs for 24 hours of the grid, $C(t)$ is the forecasted cost at hour t in next day for the grid, and $unschedulable(t)$ is the unschedulable part of the load at each DSM bus. The electricity cost can never be zero aat any instant of time.

$Connect(t)$ is given as:

$$\begin{aligned} Connect(t) = \sum_{i=1}^{t-1}\sum_{k=1}^{D} X_{kit}.P_{1k} + \\ \sum_{l=1}^{j-1}\sum_{i=1}^{t-1}\sum_{k=1}^{D} X_{ki(t-l)}.P_{(1+l)k} \end{aligned} \tag{13}$$

where, X_{kit} is the number of devices of type k that were shifted from time interval i to time interval t, D is the total number of types of devices, P_{1k} and $P_{(1+l)k}$ are the power consumption of device k in the time interval 1 and $(1+l)$ respectively, and j is the total duration of consumption of device type k.

$Disconnect(t)$ is given as:

$$\begin{aligned} Disconnect(t) = \sum_{q=t+1}^{t+m}\sum_{k=1}^{D} X_{ktq}.P_{1k} + \\ \sum_{l=1}^{j-1}\sum_{q=t+1}^{t+m}\sum_{k=1}^{D} X_{k(t-l)q}.P_{(1+l)k} \end{aligned} \tag{14}$$

where, X_{ktq} is the number of devices of type k that were delayed from time interval t to time interval q and m is the maximum allowable delay.

This objective is subject to the following constraints:
The number of devices shifted cannot have a negative value.

$$X_{kit} \geq 0, \forall\ k, i, t \tag{15}$$

The number of devices shifted cannot be more than all the connected controllable devices taken together , at that instant.

$$X_{kit} \leq shiftable(i) \tag{16}$$

where, $shiftable(i)$ is the total number of controllable devices connected to the grid at the ith interval of time. The DSM controller allows the connection instants of the devices to be delayed only and not advance in time.

$$X_{kit} = 0, \forall\ i > t \tag{17}$$

There is a constraint in terms of the maximum delay limit that can be given to the devices,to advance their connection times from their initial schedule. Here ,we have assumed a uniform delay for all the devices.

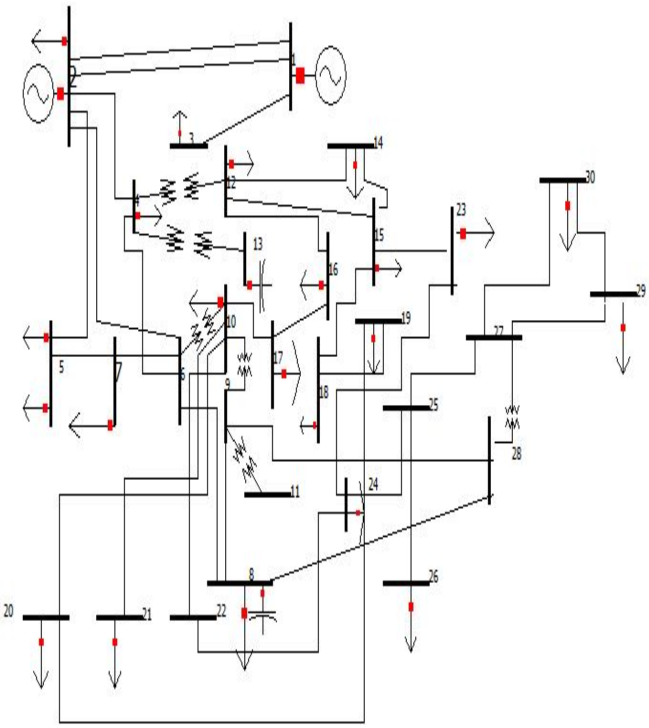

Fig. 2. IEEE 30 Bus System

$$X_{kit} = 0, \forall\ (t-i) > m \tag{18}$$

where, m is the maximum allowable delay for any device. Differential Evolution is used to get the optimal day ahead schedule .

VI. Reliability Evaluation Technique

A. Real and Reactive Power Load Shedding

The two-stage load shedding process followed distinguishes the reliability indices due to reactive power and real power shortages.This gives the necessary information to power system planners regarding the location of PQ resources for the future. Stage 1) The total available system real power capacity P_i is compared with system real power demand P_{di} including line losses also.AC power flow is performed for each contingency state i.If P_i is less than P_{di},real power loads at all load buses are curtailed according to proportional load shedding.Reactive power loads are also curtailed corresponding to initial power factor. Stage 2) Now perform AC power flow analysis again. Check Q injections at all PV buses.If the limits are violated,change those buses to PQ to fix their reactive power injection.If at some of the load buses,bus voltage is below its set point,considered as 0.9 in this paper,problems are related to the local reactive power shortage and load shedding needs to be done to solve

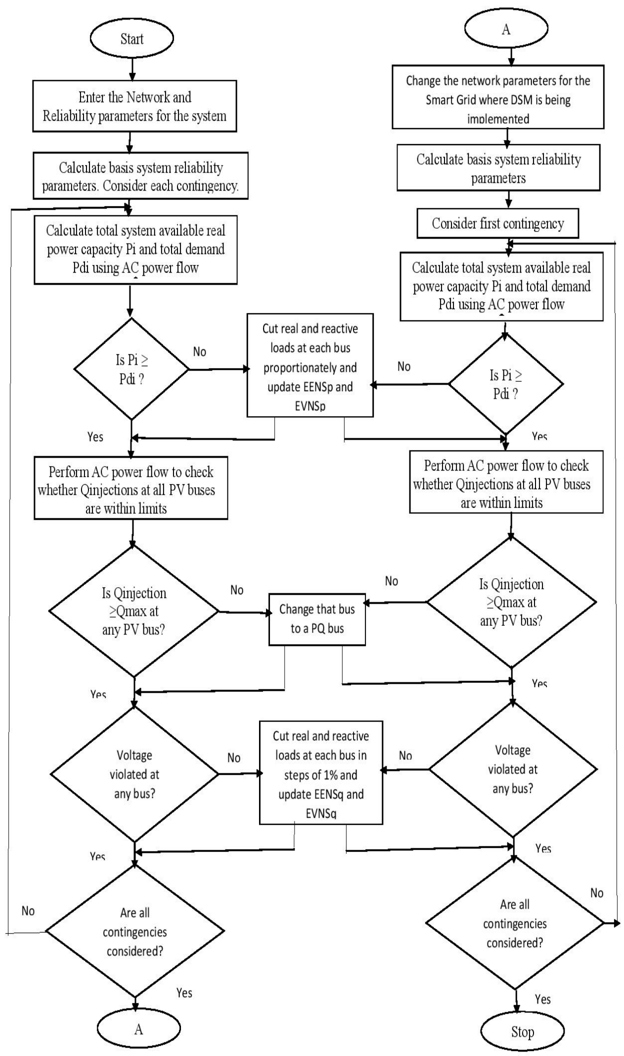

Fig. 3. Flowchart

the same.Real and reactive power loads at those buses are cut iteratively in steps of 1% with the fixed initial power factor until that bus voltage falls within the limit.This small step of 1% is selected keeping in mind that voltage is very sensitive to reactive power load.If voltage violation still exists at those buses after the loads are curtailed completely,then the loads at the adjacent buses are to be curtailed in steps according to the local characteristics of reactive power.In the case of states with isolated buses,those loads cannot be supplied.The flowchart is shown in Fig 3.Here we have considered all first order and second order contingencies.There are two types of system states 1) Those with isolated buses due to line failures,which are considered.2) Those without isolated buses-We have considered all cases except those which would require a major load shutdown,as that is not the aim of a DSM program.

TABLE I
RELIABILITY PARAMETERS AND REACTIVE POWER LIMITS

Component	Qmin	Qmax	λ	μ
Generator at Bus 1	-20	25	6	194.67
Generator at Bus 2	-20	20	4.5	219
Compensator at Bus 5	-20	25	6	194.67
Compensator at Bus 8	-10	25	6	194.67
Compensator at Bus 11	-6	20	6	194.67
Compensator at bus 13	-6	20	6	194.67

TABLE II
RELIABILITY PARAMETERS OF TRANSMISSION LINES

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

VII. SYSTEM STUDIES

Reliability indices corresponding to real and reactive power shortages are compared by analyzing the modified IEEE 30 bus system [18] and the same system where day ahead DSM is in operation.The single line diagram of the system is shown in the Fig. 2.This system has 24 PQ buses and 5 PV buses.This system was selected due to the high requirement of reactive power because of the location of remote loads and the two generators.The system active and reactive power peak loads are 283.4 MW and 126.2 MVAr respectively,in the normal state.In order to consider generator reliability in the evaluation , we have considered 4×60 MW units to be connected in Bus 1 and 3×40MW units to be connected in Bus 2.The reliability parameters for the generators,transmission lines and reactive power compensators [19] are shown in tables I and II. To make this system into a smart grid we assume that at 3 different buses in the system , DSM is in operation . Bus 30 is considered as a residential bus with a maximum of 12 hour delay for any device in the bus.We take Bus 21 as an industrial bus and bus 12 as a commercial bus and the maximum delay given to any device in these buses is 6 hours. It is known that higher the delay available for each appliance,better will be the performance of the DSM

TABLE III
FORECASTED ELECTRICITY PRICES FOR THE NEXT DAY

Time	Price(ct/kWh)	Time	Price(ct/kWh)
08h-09h	12	20h-21h	8.35
09h-10h	9.19	21h-22h	16.44
10h-11h	12.27	22h-23h	16.19
11h-12h	20.69	23h-24h	8.87
12h-13h	26.82	24h-1h	8.65
13h-14h	27.35	1h-2h	8.11
14h-15h	13.81	2h-3h	8.25
15h-16h	17.31	3h-4h	8.10
16h-17h	16.42	4h-5h	8.14
17h-18h	9.83	5h-6h	8.13
18h-19h	8.63	6h-7h	8.34
19h-20h	8.87	7h-8h	9.35

algorithm. Forecasted hourly wholesale electricity prices is given in table III.Hourly consumption of each of the three DSM buses are generated from the annual peak load and the hourly,daily and monthly percentages [19].The data of week 23 on a Tuesday 8 am to Wednesday 8 am was selected for the study.The residential,commercial and industrial areas have different types and number of controllable devices as shown in tables IV,V,VI.

TABLE IV
CONTROLLABLE DEVICES ON THE RESIDENTIAL BUS

Device Type	Quantity	Hourly Consumption (kW)		
		1st hour	2nd hour	3rd hour
Dryer	189	1.2	0	0
Dish Washer	288	0.7	0	0
Washing Machine	268	0.5	0.4	0
Oven	279	1.3	0	0
Iron	340	1.0	0	0
Vacuum Cleaner	158	0.4	0	0
Fan	288	0.2	0.2	0.2
Kettle	406	2.0	0	0
Toaster	48	0.9	0	0
Rice Cooker	59	0.85	0	0
Hair Dryer	58	1.5	0	0
Blender	66	0.3	0	0
Frying Pan	101	1.1	0	0
Coffee Maker	56	0.8	0	0

TABLE V
CONTROLLABLE DEVICES ON THE COMMERCIAL BUS

Device Type	Quantity	Hourly Consumption (kW)		
		1st hour	2nd hour	3rd hour
Water Dispenser	1560	2.5	0	0
Dryer	1170	3.5	0	0
Kettle	1230	3.0	2.5	0
Oven	770	5.0	0	0
Coffee Maker	990	2.0	2.0	0
Fan AC	930	3.5	3.0	0
Air Conditioner	560	4.0	3.5	3.0
Lights	870	2.0	1.75	1.5

TABLE VI
CONTROLLABLE DEVICES ON THE INDUSTRIAL BUS

Device Type	Quantity	Hourly Consumption (kW)					
		1st hour	2nd hour	3rd hour	4th hour	5th hour	6th hour
Water Heater	39	12.5	12.5	12.5	12.5	0	0
Welding Machine	35	25	25	25	25	25	0
Fan AC	16	30	30	30	30	30	0
Arc Furnace	8	50	50	50	50	50	50
Induction Motor	5	100	100	100	100	100	100
DC Motor	6	150	150	150	0	0	0

VIII. RELIABILITY ANALYSIS

The fixed reactive power limits for the generators and compensators as in table 5 is used for the analysis.During load shedding,the real and reactive power load at each bus is bundled together using fixed initial power factor [18].

TABLE VII
LOAD POINT AND SYSTEM $EENS_P$(MWH/YR) AND $EENS_Q$ (MWH/YR) WITH AND WITHOUT DSM

Bus	For the normal Grid		For the Smart Grid with DSM	
	$EENS_P$	$EENS_Q$	$EENS_P$	$EENS_Q$
2	588.0676	0	554.4264	0
3	65.0645	0.0254	61.3438	0.0248
4	205.9591	0	194.1769	0
5	2553.7824	13.3802	2407.7453	13.1690
7	617.8775	1.47886	582.5309	1.4787
8	813.4614	0.4646	766.9527	0.4646
10	157.1793	0.0289	148.1876	0
12	303.5187	0.3774	270.4791	0.1952
14	168.1153	0.6407	158.5035	0.4141
15	222.2191	0	209.5067	0
16	94.9038	0.0562	89.4778	0.0562
17	244.3637	0.4646	230.4111	0.4646
18	86.7196	1.9603	81.7587	0.8833
19	257.5961	0.2004	242.8683	0.2004
20	59.6197	0	56.2091	0
21	475.1516	2.7137	373.1776	1.8291
23	86.7692	0.0495	81.8082	0.0495
24	235.7691	0	222.2815	0
26	101.3966	8.5378	95.9657	8.5378
29	65.0397	2.6728	61.3190	0.4515
30	287.8061	3.4948	262.8304	1.8027
System	7690.3809	36.5469	7151.9612	30.0228

When DSM was implemented in the system,the peak loads at bus 12 ,bus 21 and bus 30 got reduced to 10.584+j7.0875 MVA,14.565+j9.3216MVA and 14.565+j9.3216MVA respectively . The reduced reactive power values of the loads were obtained as the loads were assumed to be bundled with the fixed initial power factor. The load point and system $EENS_P$ and $EENS_Q$ are shown in table VII and $EVNS_P$ and $EVNS_Q$ are shown in table VIII for the normal grid and for the smart grid where DSM is already in operation and when the voltage set point is taken as 0.9 pu.It can be seen that the load point and system $EENS_P$, $EENS_Q$,$EVNS_P$ $EVNS_Q$ are reduced in a system where DSM is in operation by 7,17.86,7.45,20.36 percentages respectiely for the DSM penetration of 10.91%. We can see that $EENS_Q$ and $EVNS_Q$ have also reduced

TABLE VIII
LOAD POINT AND SYSTEM $EVNS_P$ (MVARH/YR)AND $EVNS_Q$(MVARH/YR) WITH AND WITHOUT DSM

Bus	For the normal Grid		For the Smart Grid with DSM	
	$EVNS_P$	$EVNS_Q$	$EVNS_P$	$EVNS_Q$
2	344.1686	0	324.4799	0
3	32.5322	0.0130	30.6719	0.0124
4	43.3598	0	40.8793	0
5	515.0941	12.6037	485.6386	12.3924
7	295.3888	1.4788	278.4906	1.4787
8	813.4614	0.4646	766.9527	0.4646
10	54.1997	0.0289	51.0992	0
12	203.2491	0.3774	181.1243	0.1952
14	43.3846	0.5695	40.9041	0.3429
15	67.7497	0	63.8740	0
16	48.8076	0.0298	46.0171	0.0298
17	157.4788	0.2994	148.4871	0.2994
18	24.3899	1.9603	22.9946	0.8833
19	92.1923	0.1059	86.9213	0.1059
20	18.9699	0	17.8847	0
21	304.0971	2.3885	238.8337	1.5583
23	43.3846	0.0247	40.9041	0.0247
26	66.6320	5.6105	63.0632	5.6105
29	24.3899	2.6728	22.9946	0.4515
30	51.5878	3.0456	47.1097	1.3677
System	3426.0878	31.6741	3170.5078	25.2187

because of DSM,which shows that demand side management programs are effective not only in altering real power ,but also in changing the reactive power/voltage values in the system.

IX. CONCLUSIONS

In this paper we have investigated the effects of DSM in evaluation of reliability while considering reactive power source failures also.Reliability indices are calculated separately for both the cases and are compared.We see that in the smart grid with DSM,reliability is considerably improved.This gives an insight to system planners regarding the DSM penetration percentage for improving the system reliability.

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