Probabilistic Impact of Transmission Line Switching on Power System Operating States

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***Abstract*—Power system topology control as a planned corrective action in face of contingencies and also as a measure for achieving economic gains in real time market operation has been recently studied as an enhancement in hour- and day-ahead operations. Although attractive from the reliability and economic standpoint, the attention must be paid to the impact on the power system operating states following the switching implementation to make sure the system security performance in the new migrated operating state is not jeopardized. This paper suggests a probabilistic measure to foresee the likelihood of experiencing undesirable operating state following execution of an optimal hour-ahead switching plan. The presented approach can also be helpful in selecting the most practical switching action when the optimization engine can provide multiple optimal switching scenarios. The proposed tool is tested on a modified IEEE 118-Bus Test System to demonstrate its applicability and effectiveness.**

***Index Terms*— Economic; operating state; optimization; probabilistic; security; switching; topology control.**

I. NOMENCLATURE

Subscripts are listed below for quick references.

A. *Sets*

$g \in G$	System Generators.
$k \in K$	System Transmission Lines.
$n \in N$	System Buses.
$q \in Q$	Set of optimal switching plans.

B. *Variables*

P_g^k	Power output of generator *k*.
F_k	Power flow through line *k*.
s_k	Switch action for line k (0: no switch, 1: switch).
θ_n	Bus angle at bus *n*.

C. *Parameters*

B_k	Susceptance of link *k*.
c_g	Linear generation cost of generator *g*.
d_n	Demand (in MW) at bus *n*.
M_k	M-Value for line *k*.
$P\left(S_{AS}^t, q\right)$	Probability of system alert operating state following the optimal switching plan *q* at hour *t*.
$P\left(S_{EES}^t, q\right)$	Probability of system extreme emergency state following the optimal switching plan *q* at hour *t*.
$P\left(S_{ES}^t, q\right)$	Probability of system emergency state following the optimal switching plan *q* at hour *t*.
$P\left(S_{FS}^t, q\right)$	Probability of system favorable states following the optimal switching plan *q* at hour *t*.
$P\left(S_{NS}^t, q\right)$	Probability of system normal operating state following the optimal switching plan *q* at hour *t*.
$F_k^{\max}, F_k^{\min}$	Maximum and minimum flow limit for line *k*.
$P_g^{\max}, P_g^{\min}$	Maximum and minimum limit for generator *g*.
$\theta_n^{\max}, \theta_n^{\min}$	Max. and min. bus angle difference.

II. INTRODUCTION

The research efforts on power system topology control by means of switching transmission lines may be classified in two main categories: a) a corrective mechanism in dealing with contingencies and related operating violations [1], and b) an economic tool for realizing gains in the electricity markets [2]. References [3] and [4] propose an application of transmission line switching to alleviate the operating violations such as over voltages and overloads. A branch and bound technique through the linear approximate optimal power flow (OPF) formulation is approached in [5] to relieve the system overloads. Corrective transmission switching for the same purpose but in an AC setting is proposed in [6]. A review of the application of corrective transmission topology control in response to system critical contingencies is presented in [7]. References [8] and [9] were the first attempts at a fast approach for corrective transmission line switching considering the ability to re-dispatch generation. Corrective switching tool is introduced to manage the line flow and voltage violations using a sparse inverse technique in [10] and via a binary integer programming technique in [11]. Applicability of transmission switching plan as a loss reduction and congestion management tool has also been investigated. A switching scheme is proposed in [12], [13] to minimize the system total losses and Genetic Algorithm is used in [14] to minimize the overloads for congestion management via switching implementation. Transmission switching has been also researched to improve the system security when coupled to the unit commitment and expansion planning decision making [15], [16]. Moreover, optimal transmission switching adapted with voltage security and employing N-1 contingency analysis has been approached in [17]. Most recently, the application of transmission switching in emergency scenarios to avoid load shedding or maximize the load shed recovery is investigated in [18], [19].

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The concept of incorporating the control of transmission assets by transmission line switching has not been solely limited to the emergency scenarios. The transmission switching concept coupled with the dispatch optimization for economic benefits has been introduced in [20] and further followed in [21]. A sensitivity assessment of the optimal transmission switching problem is studied in [22]. Reference [23] presented the optimal transmission switching incorporating the N-1 generation and transmission contingency analysis. Economic assessment of optimal transmission topology control is introduced in [24]. Benefits of topology control in presence of market realizations, revenue adequacy problems, and financial transmission rights are extensively explored in [25]. Impact of optimal topology control on system reliability is investigated in [26] and some practical insights required for safe implementation of this technology in practice are suggested in [27].

This paper suggests a probabilistic decision making support tool aimed at helping the operator in deciding whether to adopt an hour-ahead optimized switching plan depending on how it affects the post-switching operating state. Section III addresses the switching optimization problem for economic benefits and the concept of power system operating states. Section IV introduces the suggested decision making support tool. Case study on the modified IEEE 118-Bus test system is demonstrated in Section V and conclusions are given in Section VI.

III. BACKGROUND

A. Optimal Transmission Switching

Power system topology control strategy can be employed through transmission line switching when the system is in the normal operating state mainly for the sake of economic benefits. It has been shown that topological reconfiguration of the transmission system could improve the efficiency of power system operations by enabling re-dispatch of the lower-cost generator [20]. The non-emergency topology control optimization is a mixed integer linear programming (MILP) problem which strives to optimize the costs of generation dispatch by representing the flexibility of transmission lines with binary variables as formulated in (1), subject to system and operating constraints in (2) [20].

$$\begin{aligned}&\min \ \sum_g c_g \overline{P_g}\\ &s.t.\end{aligned} \tag{1}$$

$$\theta_n^{\min} \le \theta_n \le \theta_n^{\max} \qquad \forall n \tag{2.a}$$

$$P_{ng}^{\min} \le \overline{P_{ng}} \le P_{ng}^{\max} \qquad \forall g, \forall n \tag{2.b}$$

$$F_k^{\min}.\alpha_k \le F_k \le F_k^{\max}.\alpha_k \qquad \forall k \tag{2.c}$$

$$\sum_k F_{nk} + \sum_g \overline{P_{ng}} = \sum_d \overline{P_{nd}} \qquad \forall n \tag{2.d}$$

$$B_k(\theta_n - \theta_m) - F_{nk} + (1-\alpha_k)\times \mathrm{M}_k \ge 0 \qquad \forall k \tag{2.e}$$

$$B_k(\theta_n - \theta_m) - F_{nk} - (1-\alpha_k)\times \mathrm{M}_k \le 0 \qquad \forall k \tag{2.f}$$

$$\alpha_k \in \{0,1\} \qquad \forall k \tag{2.g}$$

The Direct Current Optimal Power Flow (DCOPF) mechanism accommodated by transmission switching is presented in (1) and (2) as the optimization engine. However, the optimization problem based on the AC settings can be employed as well, if the computational facilities allow. Voltage angle limits are imposed by (2.a) and are set to 0.6 and -0.6 radians for upper and lower constraints, respectively. The output power of generator g at node n is limited to its physical capacities in (2.b). Constraint (2.c) limits the power flow across line k. Constraint (2.d) ensures the power balance at each system bus and Kirchhoff's laws are enforced in (2.e) and (2.f). According to (2.g), α_k is an integer variable demonstrative of the offline ($\alpha_k = 1$) and online ($\alpha_k = 0$) status of any line k of the system. The parameter M is a user-specified large number commonly selected to satisfy the following equation:

$$\mathrm{M}_k \ge B_k(\theta_n^{\max} - \theta_m^{\min}) \qquad \forall k \tag{3}$$

The objective of the above-introduced optimization engine is minimizing the generation dispatch cost by an hour-ahead selection of the lines to be switched based on the generation patterns obtained through unit commitment practices and predicted load profiles at each hour.

B. Power System Operating States

The ability of an electric power system to meet the required load demand and withstand the probable disturbances is commonly described through a representation of several operating states which are mutually exclusive. Such system operating states, which actually demonstrate the system performance in terms of the degree to which reliability constraints are satisfied, are depicted in Fig. 1 and defined as follows [29]:

- The *normal* operating state. In this state, the power system generation adequacy is guaranteed and the total generation level is adequate to supply the requested load demand. Also, there is sufficient operating margin in this state so that loss of any generating unit would not cause any load interruption.
- The *alert* operating state. In this state, a power system may experience a condition in which loss of generating capacity may lead to some load curtailments. The alert operating state is analogous to the normal state as the system balance limits are satisfied but there is no longer enough margin available to survive any further contingencies.

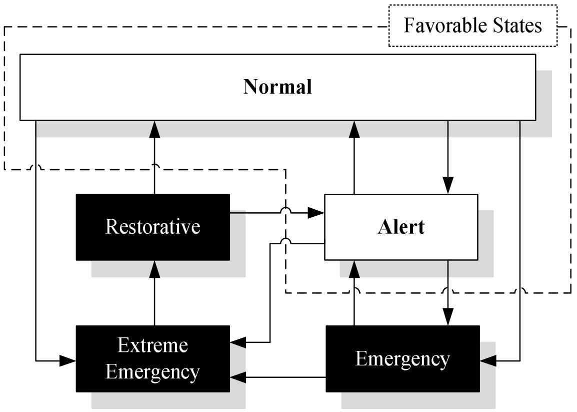

Figure 1. Power system operating states diagram.

- The *emergency* operating state. In this state, if a contingency happens, the reserve margin is not available meaning that the operating capacity is exactly equal to the demand. Also, the transient stability or the steady-state stability margins may be low enough for a contingency to violate the system security.
- The *extreme emergency* operating state. In this state, system constraints are violated and some portion of demand is interrupted, and if control actions are not adopted in time to migrate the system to the alert or normal states, a blackout or brownout will occur. Generally, the extreme emergency operating state may be further categorized as follows [30]:
  1) *Capacity emergency* where a mismatch between load, transmission, and generation exists.
  2) *Stability emergency* which is associated with a relatively short time frame and emergency is concerned with transient instability, steady-state instability, and voltage instability.
  3) *Integrity emergency* which is usually a result of any of the preceding two types of emergencies. A capacity emergency may cause line trips due to overloads. Stability emergency may also lead to line tripping and hence the system may collapse.

IV. SUGGESTED DECISION SUPPORT TOOL

Variations due to the stochastic nature of renewable power generation such as wind and solar, as well as stochastic response of the load could definitely change the probability of the migration to various operating states after a change in the system topology takes place. The suggested operator decision making support tool will calculate the probability of migration to each system operating state after an optimized switching plan is implemented. The switching implementation for economic benefits should take place in the normal operating state and adopting such actions for financial gains can only be justifiable to the operator when the probability of system migrating to an emergency or extreme emergency operating state following the switching implementation itself is very low. However, the possibility of contingencies in the state immediately following the switching implementation still exists and if happens, the system might be more likely to migrate to emergency or even extreme emergency states.

The probability index value for the system extreme emergency state is calculated as the highest probability that a transmission line is overloaded over 120% compared to the nominal value and is defined as follows:

$$P\left(S_{EES}^{t},q\right)=\max_{k\in K,q\in Q} P_{t}\left(F_{k} \geq 1.2F_{k}^{\max}\right) \tag{4}$$

The probability index value for the system emergency state is calculated as the highest probability that the power flow of a transmission line is higher than the line rating, but lower than 120%, and is defined as follows:

$$P\left(S_{ES}^{t},q\right)=\max_{k\in K,q\in Q} P_{t}\left(F_{k}^{\max} \leq F_{k} \geq 1.2F_{k}^{\max}\right) \tag{5}$$

The favorable states the operator would like the system to migrate to after a switching line implementation is either the normal or alert state for a short period of time (one hour), as demonstrated in Fig. 1. The higher the probability of such states after the switching implementation, the more favorable the switching solution would be. The probability of the system experiencing such favorable states is calculated as follows:

$$P\left(S_{FS}^{t},q\right)=P\left[\left(S_{NS}^{t}+S_{AS}^{t}\right),q\right]=1-\left[P\left(S_{ES}^{t},q\right)+P\left(S_{EES}^{t},q\right)\right] \tag{6}$$

In order to evaluate the probability of the alert state after switching implementation, power flow results in the N-1 situation is being utilized. This probability, which is actually a conditional probability under the condition that it is already a part of the favorable operating sate calculated in (6), can be calculated as follows:

$$P\left(S_{AS}^{t},q\right)=P\left(S_{FS}^{t},q\right).\left(\max_{k\in K,q\in Q} P_{t}\left(F_{k}^{N-1} \geq F_{k}^{\max}\right)\right) \tag{7}$$

And finally the probability of system normal state would be calculated as follows:

$$P\left(S_{NS}^{t},q\right)=P\left(S_{FS}^{t},q\right).\left(1-P\left(S_{AS}^{t},q\right)\right) \tag{8}$$

As a result of the above classification of power system states, the following properties need to be guaranteed.

$$P\left(S_{x}^{t},q\right)\in[0,1] \tag{9.a}$$

$$P\left(S_{NS}^{t},q\right)+P\left(S_{AS}^{t},q\right)+P\left(S_{ES}^{t},q\right)+P\left(S_{EES}^{t},q\right)=1 \tag{9.b}$$

By using the power flow results for topology control plans and considering both N and the N-1 reliability requirements, the probabilistic measure of each system state can be calculated and as a result, various optimized transmission switching solutions can be compared and prioritized. The operator will be able to select the one which leads to the system favorable states (normal or alert) with higher probability values.

V. CASE STUDY: IEEE 118-BUS TEST SYSTEM

The IEEE 118-bus test system is adjusted and modified to represent a case study in which there are a total of 186 transmission lines and 19 generators, with the installed capacity of 5859.2MW, serving a total demand of 4519MW [31]. The system data including the transmission line and generating unit parameters are available in [28]. The MILP optimization problem, i.e., the optimal transmission switching problem with the main objective of generating cost minimization, is solved in the GAMS and MATLAB environment [32], [33] and using the equation set (1)-(3) based on the DCOPF formulation. The master optimization problem is run on a PC with an Intel(R) Xeon(R) 3.2 GHz processor and 12 GB of RAM resulting in the optimal generation dispatch as well as the optimal status of transmission lines. The bus voltage angles all over the system are constrained to -0.6 and +0.6 radians for the lower and upper limits, respectively. Several optimal switching solutions to the problem can be obtained taking into account different values for the maximum number of switchable lines (for an hourly generation and load profile). The optimization results obtained for the case study on the modified IEEE 118-bus test system are tabulated in Table I. The table demonstrates the first 6 optimal strategies which are the most economically attractive considering at most 2 switching possibilities per hour. It can be seen from the results in

TABLE I
OPTIMAL LINE SWITCHING SOLUTIONS: IEEE 118-BUS TEST SYSTEM

Cases	Switching Lines	Generation Dispatch Cost ($/h)	Cost Savings (%)
1	-	2053.08	-
2	153	1924.53	6.26
3	132	1930.63	5.96
4	153, 132	1795.92	12.52
5	153,165	1811.25	11.78
6	132,136	1779.05	13.35
7	132,165	1797.01	12.47

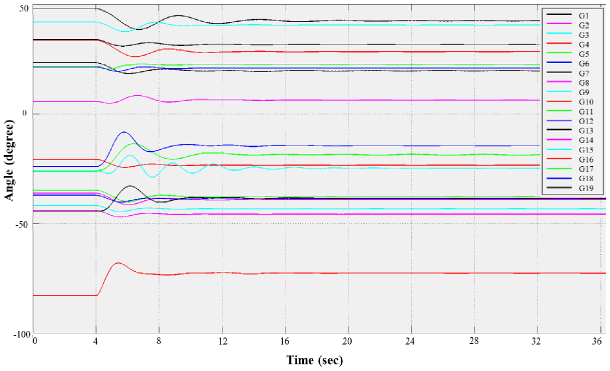

Figure 2. Relative generator rotor angle plots after switching implementation in case 4.

Table I that if economically looking for the optimal solution, a more attractive solution may be possible by allowing more than one switching action to happen (i.e., taking more than one line out in an hour). However, the technical performance of the system must be also taken into consideration so that the switching solutions do not jeopardize the system security and reliability criteria. Since the optimization engine is formulated based on the DCOPF, and in order to account for the voltage magnitudes and reactive power, the switching solutions have been tested under both AC feasibility and transient stability checks. All the 6 solutions have passed the AC feasibility and stability checks. The result of transient stability check for solution case 4 (switching out lines 153 and 132) is demonstrated in Fig. 2, which shows the system settles down smoothly after switching implementation without causing any stability issues.

The results of the suggested probabilistic analysis for the system base case (case 1 with no switching implementation) are demonstrated in Fig. 3. From the calculated probability of various operating states presented in this figure, it can be inferred that the system base case condition is healthy as $P\left(S_{NS}^{t}+S_{AS}^{t}\right)\geq 98.5\%$. The probabilistic measures of each operating state after implementation of various optimal switching scenarios are demonstrated next in Fig. 4 to Fig. 7, which illustrate the probability of experiencing the normal, alert, emergency, and extreme emergency states of the system, respectively. From the results, it can be seen that various optimal switching scenarios have different impacts on the power system normal operating state. For instance, the optimized switching option in case 3 would be a more reliable solution than the others in that the associated possibility of experiencing the favorable states (normal and alert) is higher than that of the other options (i.e., 97%). The results also demonstrate that the optimized scenarios with more transmission lines involved would result in the system conditions in which the probability of emergency and

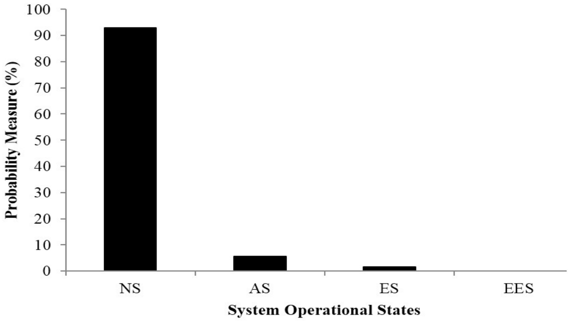

Figure 3. Operating state probabilities of the system- Base Case.

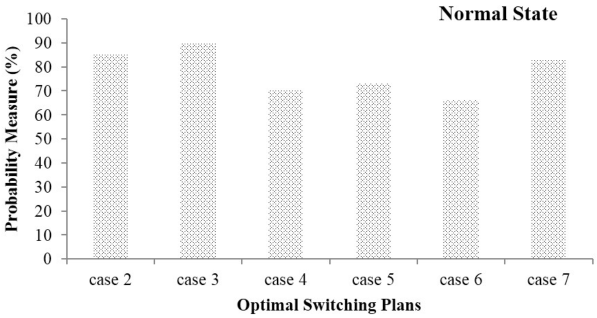

Figure 4. Probability of normal operating state for the studied cases.

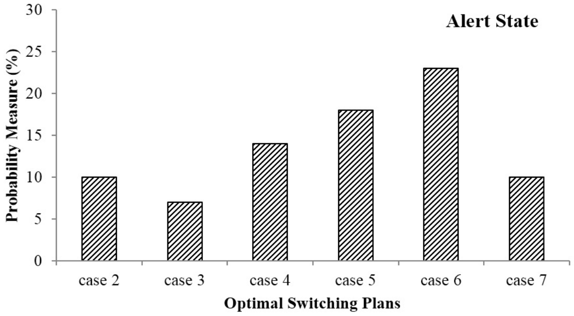

Figure 5. Probability of alert operating state for the studied cases.

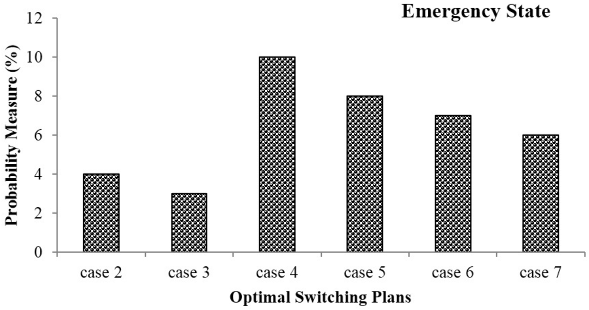

Figure 6. Probability of emergency operating state for the studied cases.

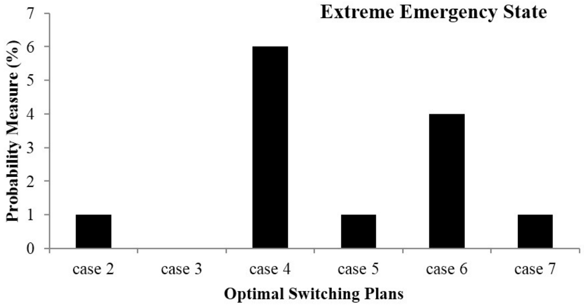

Figure 7. Probability of extreme emergency operating state for the studied cases.

extreme emergency states would increase. As a consequence, a compromise needs to be reached between the cost savings when more switching actions are taken and the probability of reaching undesirable operating states. The operator can use such information to decide on the implementation of the switching plan (or plans).

VI. CONCLUSIONS

The paper accomplishes the following:

- A probabilistic approach which accounts for the impact of transmission switching implementation on the probability of experiencing various post-state operating conditions is proposed.
- The suggested decision making support tool helps the operator to decide whether an optimal switching plan is a viable solution at each hour under various market conditions judging whether it also ensures a subsequent safe/secure system topology.
- With the increased trend of renewable generation penetration and stochastic nature of the load and generation, such analysis results in an operator support tool that is essential for a reliable decision making when performing topology switching.

VII. ACKNOWLEDGEMENT

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