Impact Assessment of Transmission Line Switching on System Reliability Performance

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Abstract— **Power system topology control through transmission line switching for economic gains has been recently considered for day to day operations. This paper investigates the impact of various DC and AC optimal switching solutions on the system-wide reliability indices. Probabilistic performance indices of the system reliability, e.g., expected energy not supplied (EENS), customer interruption costs (CIC), delivery point unreliability index (DPUI), and loss of load probability (LOLP), are utilized to assess the robustness of the new migrated system state after implementation of switching plans from the reliability viewpoint. The information of such studies will help the operator evaluate the economic benefits and system reliability requirements and decide whether to implement the optimal switching solutions at each hour. The approach is tested using a modified IEEE 118-Bus test system and the results revealed its applicability and efficiency.**

Index Terms— **Economics; reliability indices; optimal power flow (OPF); reliability; switching; topology control.**

I. NOMENCLATURE

Subscripts are listed below for quick references.

A. Sets

$d \in D$	System demands
$g \in G$	System generators.
$h \in \Psi$	System contingencies.
$k \in K$	System transmission lines.
$n \in N$	System buses.
$q \in Q$	Optimal switching plans at time t.
$s \in S$	System states with load curtailment.

B. Variables

F_k, F_{knm}	Active power flow through line k connecting bus n to bus m.
P_{ng}	Active power output of generator g at bus n.
Q_{knm}	Reactive power flow through line k connecting bus n to bus m.
Q_{ng}	Reactive power output of generator g at bus n.
V_n	Voltage at bus n.
α_k	Switch action for line k (0: no switch, 1: switch).
θ_n	Bus angle at bus n.
θ_{nm}	Bus angle difference between bus n and bus m.

C. Parameters

B_k, B_{nm}	Susceptance of link k between bus n and bus m.

b_{nm}^p	Shunt susceptance of line k between bus n and bus m.
c_g	Linear generation cost of generator g.
d_n	Demand (in MW) at bus n.
F_k^{max}, F_k^{min}	Max. and min. active line flow limit for line k.
G_{nm}	Conductance of link k between bus n and bus m.
$\mathrm{IL}_{i,h,q}^t$	Interrupted load (MW) at bus i due to contingency h in the case of system optimal topology q at time t.
M_k	M-Value for line k.
OD_h^t	Outage duration of contingency h at time t.
P_D^{max}	Annual peak load demand of the system.
P_h^t	Probability of contingency h at time t.
P_{nd}	Active power demand at bus n.
$P_{ng}^{max}, P_{ng}^{min}$	Max. and min. generation limit for generator g.
$\mathrm{Pr}_{s,q}^t$	Probability of system state s in the case of system optimal topology q at time t.
Q_{nd}	Reactive power demand at bus n.
$Q_{ng}^{max}, Q_{ng}^{min}$	Max. and min. reactive power of generator g.
S_k^{max}	Max. flow of the apparent power on line k.
V_n^{max}, V_n^{min}	Max. and min. of the voltage at bus n.
VOLL_i	Value of Lost Load at bus i.
$\theta_n^{max}, \theta_n^{min}$	Max. and min. bus angle difference at bus n.

D. Indices

$\mathrm{CIC}_{TS,q}^t$	CIC index of the transmission system in the case of system optimal topology q at time t.
$\mathrm{DPUI}_{TS,q}^t$	DPUI index of the transmission system in the case of system optimal topology q at time t.
$\mathrm{EENS}_{i,q}^t$	EENS index at bus i in the case of system optimal topology q at time t.
$\mathrm{EENS}_{TS,q}^t$	EENS index of the transmission system in the case of system optimal topology q at time t.
$\mathrm{LOLP}_{TS,q}^t$	LOLP index of the transmission system in the case of system optimal topology q at time t.

II. INTRODUCTION

Power system topology control through transmission line switching has been acknowledged as an effective approach that can be employed in the system normal operating state. In such scenarios, transmission line switching is adopted majorly for the sake of higher grid economic efficiency and

financial gains by exploiting and harnessing the network infrastructure [1]. The reason lies in the fact that having solely one single optimal topology for the network in all operation time periods with all different possible market realizations is rarely imaginable. Hence, harnessing the grid topology coupled to economic dispatch optimization in some cases may bring about potentials for huge economic savings [2]. Topology control can also play a critical role when applied in the system emergency scenarios where it helps mitigating a contingency state either by alleviating the overload congestion or preventing the load shedding. It has been proven both in theory and practice that removing a line out in some contingency cases may lead to a faster and effective remedy [3], [4]. Accordingly, the research efforts on power system topology control covers two categories: a) application of corrective topology control actions in mitigating the contingencies and overflows, and b) transmission switching technology as an economic tool for achieving considerable financial gains.

Regarding the first category, methods described in [4], [5] for corrective transmission switching to alleviate overload conditions are proposed. Similarly, the branch and bound technique is utilized in [6] through an approximate and linear optimal power flow (OPF) formulation to relieve the system overloads. Corrective transmission switching for the same purpose but in an AC setting is proposed in [7]. Overviews on the use of corrective transmission switching in dealing with probable contingencies are presented in [8], [9]. While most of such attempts acknowledged the benefits of switching strategies in emergency scenarios, they mostly did not delve into co-optimizing the flexibility of the transmission grid with the ability to perform generation re-dispatch. References [10] and [11] were the first attempts that presented a fast approach for corrective transmission switching with harnessing the control over the transmission components considering the ability to re-dispatch generation. Corrective switching tool is introduced to mitigate the possible voltage violations and line overload conditions using a sparse inverse technique in [12] and via a binary integer programming technique in [13]. Applicability of transmission switching plan as a loss improvement and congestion management tool has also been investigated in literature. A switching scheme to minimize the system total losses is proposed in [14], [15] and Genetic Algorithm is used in [16] to minimize the amount of overloads for congestion management through switching implementation. Transmission switching has been also researched to improve the system security when coupled to the unit commitment and expansion planning decision making [17]-[19]. Moreover, optimal topology control decisions taking into account the voltage security has been approached in [20]. Most recently, the application of transmission switching in emergency scenarios to recover the maximum from performing the load shedding [21], and to improve the system reliability [22] are also investigated. It was concluded in [23] that 17% of the N-1 contingencies which have violations can be eliminated through topology control and 7.3% of the contingencies are not affected by the corrective topology control plans.

The concept of incorporating the control of transmission assets has not been solely limited to the emergency scenarios. As a radical step to the research in this area, transmission switching concept coupled with dispatch optimizations for economic benefits has been introduced in [24] and further followed in [25]. A series of studies in recent years have been conducted aimed at studying the impacts of optimal topology control on the grid techno-economic efficiency when power system is in its normal non-emergency operating state. Among the available literature, some sensitivity analysis and extended studies are conducted in [26] for the optimal topology control problem. Reference [27] presented the optimal transmission switching with N-1 generation and transmission contingency analysis. Commitment optimization of transmission facilities together with generation assets was also extended in [28]. Economic analysis of optimal topology control strategies is introduced in [29]. Benefits of topology control in presence of market realizations, revenue adequacy problems, and financial transmission rights are extensively explored in [30]-[33]. Last but not least, computational burden of the optimal transmission switching problem, which may question its practical attractiveness, has recently motivated several researches to use advanced optimization techniques and heuristics [34]-[38].

The decisions for day-to-day frequent transmission line switching for economic gains, however, are currently not widely adopted in practice by the operator. This is either due to the operator not trusting the theoretical solutions, or the operator preference to rather do it manually for already known conditions than in an automated and systematic manner for any conditions that may warrant this action. Although economically attractive, the switching solutions might migrate the current system state to new states with different levels of reliability. Different from the previous literature that studied the applicability of the N-1 criterion for switching decision making and the validity of the optimal results under such circumstances, this paper tries to study the impact of switching implementation on system-wide reliability indices. The common N-1 criterion considers the system capable of withstanding every single component failure. However, the N-1 standard neglects the component probability of failure, and does not take into account the possible multiple contingencies that may lead to a cascade resulting in a catastrophic blackout. Switching decisions under such probabilistic considerations need to be well thought by taking into account the solar and wind uncertainties and the stochastic nature of the load demand. The common probabilistic reliability indices are evaluated for various optimal switching solutions to provide the operator with the support information required for practical implementation of the switching actions. Based on such analysis, the operator can decide whether to adopt the optimized switching plan in any hour depending on how it affects the switched topology post-state. In other application, the suggested solution will help the operator to decide which switching plans to implement among a set of multiple switching options. Such information will help the operator to keep the balance between the economic savings and technical reliability performance requirements of the system.

The background on the DC and AC switching optimization problem for economic gains is discussed in Section III. Section IV introduces the concept of power system reliability and the system-wide reliability performance indices. Case study on the modified IEEE 118-Bus test system is demonstrated in Section V and conclusion are at the end.

III. BACKGROUND

A. Optimal Transmission Switching - DC Setting

It has been demonstrated in previous literature that topological reconfiguration of the transmission system could improve the efficiency of power system operations by enabling re-dispatch of the lower-cost generators [2]. The non-emergency topology control optimization in DC setting is a mixed integer linear programming (MILP) problem which tries to optimize the generation dispatch costs taking into account the flexibility of transmission lines with binary variables. This single-objective optimization problem is formulated in (1), subject to several system constraints as introduced in equation (2).

$$\min \sum_{g \in G} c_g P_g \tag{1}$$

$s.t.$

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

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

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

$$\sum_{k \in K} F_{nk} + \sum_{g \in G} P_{ng} = \sum_{d \in D} P_{nd} \qquad \forall n, \forall g, \forall d \tag{2.d}$$

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

$$B_k(\theta_n - \theta_m) - F_{nk} - (1 - \alpha_k) \times M_k \leq 0 \qquad \forall k \tag{2.f}$$

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

As can be realized, the Direct Current Optimal Power Flow (DCOPF) mechanism accommodated by transmission switching is presented in equations (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[1]. The output power of generator g at node n is limited to its capacities in (2.b). Constraint (2.c) limits the power flow across line k. Power balance is mandated by (2.d) at each bus and Kirchhoff's laws are incorporated in (2.e) and (2.f). According to (2.g), α_k is an integer variable representing the transmission lines being switched out ($\alpha_k = 1$) and in-service status ($\alpha_k = 0$) of any line k of the system. It is worthy to note that the parameter M is a user-specified large number commonly selected as to satisfy the following equation:

$$M_k \geq B_k(\theta_n^{\max} - \theta_m^{\min}) \qquad \forall k \tag{3}$$

The solutions to the above-introduced optimization problem is the minimized generation cost with the optimized lines to be switched out hourly based on the generation patterns obtained through unit commitment practices and predicted load profiles at each hour.

B. Optimal Transmission Switching - AC Setting

The AC formulation of the topology control problem (for the cost minimization objective) is introduced in equations

(4)-(5) which takes into account the voltage magnitude variables (which were set equal to 1 in the DC approximations) and the reactive power constraints which are highlighted in the bus balance equations and limit constraints for the generators and lines [38].

$$\min \sum_{g \in G} c_g P_g \tag{4}$$

$s.t.$

$$V_n^{\min} \leq V_n \leq V_n^{\max} \qquad \forall n \tag{5.a}$$

$$\theta_n^{\min} \leq \theta_n \leq \theta_n^{\max} \qquad \forall n \tag{5.b}$$

$$P_{ng}^{\min} \leq P_{ng} \leq P_{ng}^{\max} \qquad \forall g, \forall n \tag{5.c}$$

$$Q_{ng}^{\min} \leq Q_{ng} \leq Q_{ng}^{\max} \qquad \forall g, \forall n \tag{5.d}$$

$$\sum_{g \in G} P_{ng} - (1 - \alpha_k) F_{knm} = \sum_{d \in D} P_{nd} \qquad \forall k, \forall g, \forall d \tag{5.e}$$

$$\sum_{g \in G} Q_{ng} - (1 - \alpha_k) Q_{knm} = \sum_{d \in D} Q_{nd} \qquad \forall k, \forall g, \forall d \tag{5.f}$$

$$F_{knm} = V_n V_m \left(G_{nm} \cos(\theta_{nm}) + B_{nm} \sin(\theta_{nm}) \right) \\ - G_{nm} V_n^2 \qquad \forall k, \forall n, \forall m \tag{5.g}$$

$$Q_{knm} = V_n V_m \left(G_{nm} \sin(\theta_{nm}) - B_{nm} \cos(\theta_{nm}) \right) \\ + V_n^2 \left(B_{nm} - b_{nm}^p \right) \qquad \forall k, \forall n, \forall m \tag{5.h}$$

$$\left((1 - \alpha_k) F_{knm} \right)^2 + \left((1 - \alpha_k) Q_{knm} \right)^2 \\ \leq \left((1 - \alpha_k) S_k^{\max} \right)^2 \qquad \forall k \tag{5.i}$$

$$\alpha_k \in \{0,1\} \qquad \forall k \tag{5.j}$$

IV. POWER TRANSMISSION SYSTEM RELIABILITY INDICES

For the sake of comparisons and guidance among the optimal switching plans, the robustness of the system after implementation of switching actions can be considered as a criterion for decision making. The following reliability indices are employed [39]:

- Expected Energy Not Served (EENS): a combination of the outage frequency, duration, and severity. Since it carries relatively more information than the other indices, this index is chosen for comparison purposes. The probabilistic state enumeration approach is employed up to the third order of contingencies on the reconfigured system to assess the EENS as quantified in (6)-(7).

$$\text{EENS}_{i,q}^t = \sum_{h \in \Psi} P_h^t . OD_h^t . IL_{i,h,q}^t \tag{6}$$

$$\text{EENS}_{TS,q}^t = \sum_{i \in N} \text{EENS}_{i,q}^t \tag{7}$$

- Customer Interruption Cost (CIC): a function of damages and the cost of power unavailability to the customers. In other words, the damage costs to the customers due to the outages are considered as the surrogate of reliability worth and are dependent on the customer types in the delivery points. The CIC is formulated in equation (8) and can be calculated either for the entire system or at individual buses.

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[1] Upper and lower limits for voltage angle constraints are 0.6 and -0.6 radians to help in finding the solutions fast. While such bounds are selected conservatively, loosening them may result in improved solutions [25].

$$CIC_{TS,q}^t = \sum_{i \in N} EENS_{TS,i,q}^t.VOLL_i \qquad (8)$$

- Delivery Point Unreliability Index (DPUI): a measure to evaluate the performance of the overall bulk electricity system in a given time interval through a composite unreliability index. This index is measured in system minutes per year [39]. This index actually demonstrates the time duration (in minutes) it takes if the total system load interruption happens at the time of system peak load condition in order to cause the same amount of annual cumulative EENS at all load points [39]. In other words, DPUI reflects the severity of a given power source outage as a consequence of an interruption. This index is calculated as the total EENS due to the interruption events at all system load points normalized by the amount of system peak load, as formulated in equation (9).

$$DPUI_{TS,q}^t = \frac{60.EENS_{TS,q}^t}{P_D^{max}} \qquad (9)$$

- Loss of Load Probability (LOLP): a probability that a power system is not able to serve the requisite load within a desired period of time. Probabilistic state enumeration approach is pursued up to the third order of system contingencies to study the requisite number of states in the reconfigured transmission system and identify the states with the load interruptions. The LOLP index can be calculated as introduced in equation (10).

$$LOLP_{TS,q}^t = \sum_{s \in S(IL \neq 0)} Pr_{s,q}^t \qquad (10)$$

V. CASE STUDY: MODIFIED IEEE 118-BUS TEST SYSTEM

The IEEE 118-bus test system is adjusted and modified as to serve as a case study. There is a total of 185 transmission lines and 19 generators, with the installed capacity of 5859.2MW, serving a total demand of 4519MW. The peak load demand is considered to be 5400MW. The system data including the transmission line parameters, reliability data, and generator variable costs are introduced in [40]. Up to third order of contingencies is considered for the evaluation of the reliability indices in DC and AC scenarios. The optimization problems, i.e., the optimal transmission switching with the main objective of generating cost minimization, is solved in both DC and AC settings using equation set (1)-(5). While the focus of this paper is to investigate the impact of optimal switching technology on the system reliability performance, the optimization problem could be solved through a multi-objective formulation to maximize the system reliability while minimizing the system total costs. Future research is needed to co-optimize the system economic and reliability requirements. The master optimization problem and the reliability analysis were all run on a PC with an Intel(R) Xeon(R) 3.2 GHz processor and 12 GB of RAM. It allows the status of each line as well as the optimized generation dispatch to be determined. Several optimal switching solutions taking into account different values for the maximum number of switchable lines (for a given generation and load profile) may be obtained.

The optimization results for the 118-bus case study based on the DC and AC scenarios are shown in Table I. The table demonstrates the first 5 optimal switching strategies which are the most economically attractive considering at most 1 switching action per hour. Several observations are made as follows:

- Even when there is only one possibility of switching a transmission line in a given time frame (one hour), no matter whether formulated in DC or AC settings, the operator might be given several optimal solutions for switching implementation for the main sake of economic gains in that hour.
- Switching each of the optimally selected lines in the studied time frame (one hour) leads to economic savings of at least 0.75% and 0.27% compared to that of the base case respectively in DC and AC scenarios. The optimal solution with the highest cost saving is to switch line 157 (connecting bus 92 to bus 94) with the cost saving of 13.62% in the DC scenario and switch line 150 (connecting bus 88 to bus 89) with the cost saving of 2.1% in the AC scenario.
- The economic saving of switching implementation when formulated based on the ACOPF is generally observed to be less than that when formulated in DC setting. However in large scale power systems, such low percentage of cost saving will be always

TABLE I
OPTIMAL DCOPF-BASED AND ACOPF-BASED LINE SWITCHING SOLUTIONS: MODIFIED IEEE 118-BUS TEST SYSTEM

| Cases		Solution Priority	Optimal Switching Lines	FROM Bus	To Bus	Optimal Dispatch Cost ($/hr.)	Cost Saving (%)
DC Analysis	Base Case	N/A	N/A	N/A	N/A	2074.00	0
	Optimal Options	Opt. 1	157	92	94	1791.55	13.619
		Opt. 2	25	15	33	1829.14	11.806
		Opt. 3	50	30	38	1982.39	4.417
		Opt. 4	135	79	80	2029.55	2.1434
		Opt. 5	36	23	24	2058.28	0.7577
AC Analysis	Base Case	N/A	N/A	N/A	N/A	354860.00	0
	Optimal Options	Opt. 1	150	88	89	347525.33	2.0669
		Opt. 2	115	68	81	350431.88	1.2478
		Opt. 3	161	94	95	352626.90	0.6293
		Opt. 4	112	65	68	353551.94	0.3686
		Opt. 5	16	11	12	353893.39	0.2724
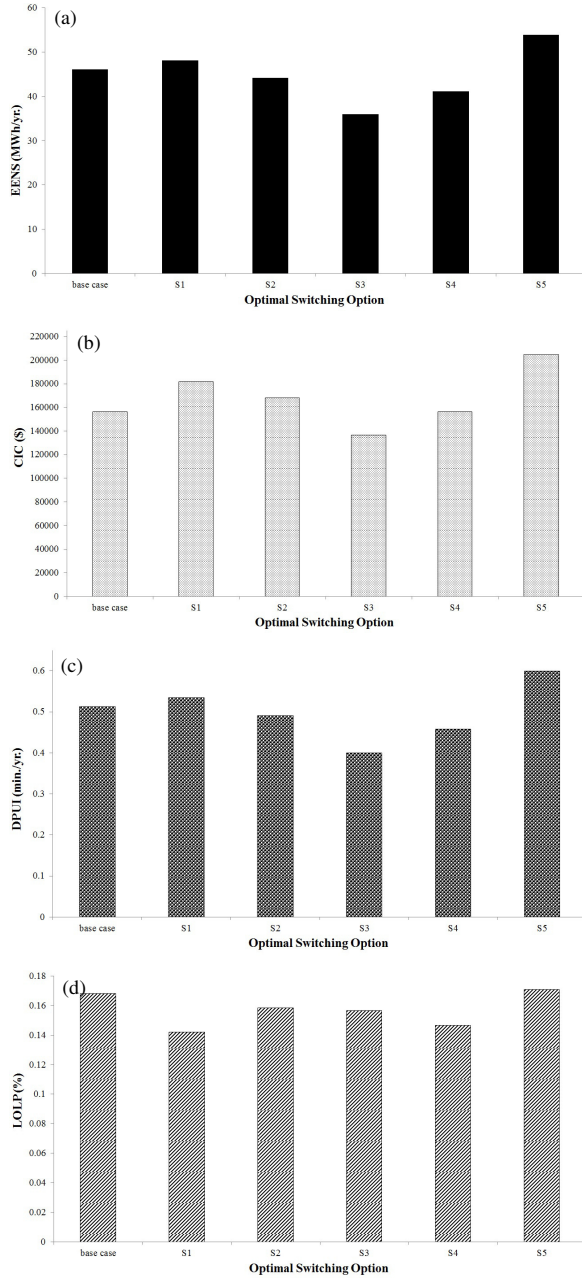
Figure 1. Transmission system reliability analysis corresponding to the DCOPF-based optimal switching cases; (a) EENS, (b) CIC, (c) DPUI, (d) LOLP.

Figure 2. Transmission system reliability analysis corresponding to the ACOPF-based optimal switching cases; (a) EENS, (b) CIC, (c) DPUI, (d) LOLP.

translated into millions of dollars.

Fig. 1 (a)-(d) demonstrates the reliability indices (EENS, CIC, DPUI, and LOLP, respectively) of the system for each of the optimal options when the switching problem is formulated in DC setting. Similarly, the reliability studies for the ACOPF-based switching cases are illustrated in Fig. 2(a)-(d). The following observations can be noted:

- Contrary to the conventional thoughts, taking transmission lines out of operation may bring about significant improvements in power system reliability indices. Comparisons of the studied reliability indices with those of the system base case proves the fact that switching some optimal lines has improved the system reliability performance (as much as 22%) while some others might sacrifice the system reliability in return for the economic gains.
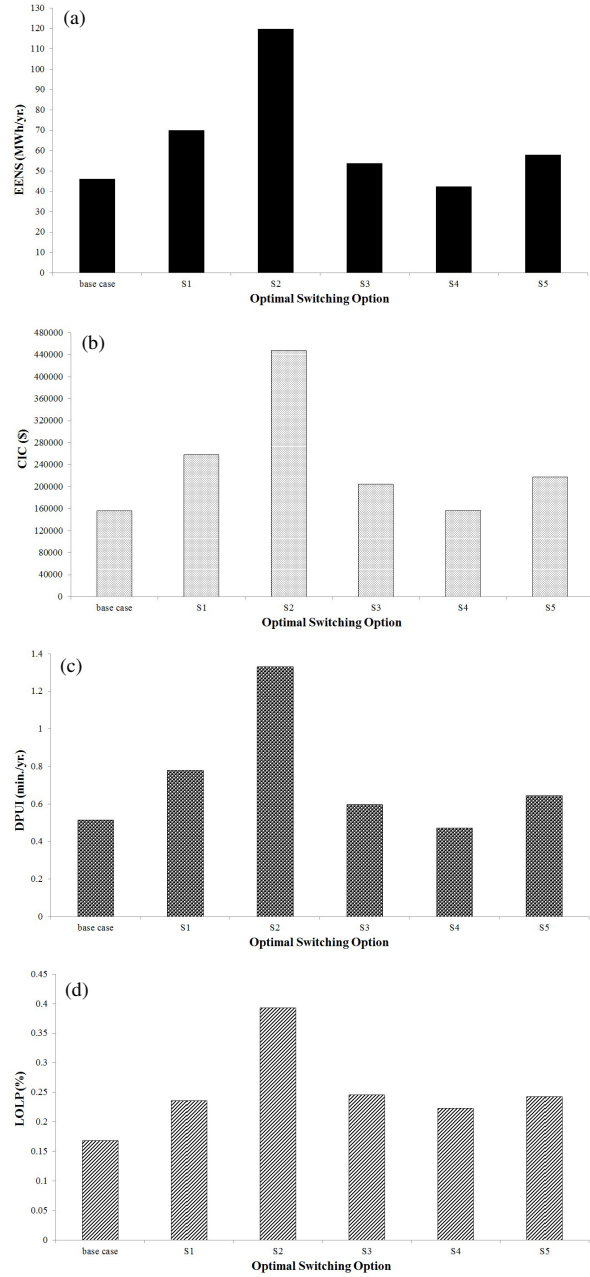
- The most economically attractive optimal switching solution may not be able to migrate the system to a reliable condition compared to the system base case and it highly depends on the reliability index of interest and the type of analysis (DC vs. AC). As a result, the operator might need to rethink his/her decision for final implementation.

- The results on this specific test system show that the switching solutions obtained in the AC analysis are generally not able to highly improve the performance indices of system reliability while those of the DC analysis are mostly successful in improving the system reliability performance. This may not be a generic conclusion though.

VI. Conclusions

The following contributions are worth pointing out:

- An assessment study of the impact of transmission line switching on system reliability indices is conducted in DC and AC optimization settings.
- The switching optimization problem is solved in such a way that the operator can be offered several switching possibilities to select among at each hour.
- The study suggested that the optimal switching may or may not improve the system reliability. The trade-off between the economic benefits and reliability requirements should be made.
- The decision making support tool for the operator helps decide whether the optimal switching plan is practically viable and suitable solution at each hour.
- With the increased trend of renewable penetration and stochastic behavior of load/generation, such analysis is essential for making effective decisions.

VII. Acknowledgement

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