Performance of AC and DC Based Transmission Switching Heuristics on a Large-Scale Polish System

Mostafa Sahraei-Ardakani, Akshay Korad, and Kory W. Hedman
School of Electrical, Computer, and Energy Engineering
Arizona State University
Tempe, AZ, USA
kory.hedman@asu.edu

Paula Lipka and Shmuel Oren
Dept. of Industrial Engineering and Operations Research
University of California at Berkeley
Berkeley, CA, USA

***Abstract*— Optimal transmission switching (OTS) has demonstrated benefits both in terms of reliability and cost savings for bulk power systems. OTS is a mixed-integer program (MIP) with binary variables representing the status of the transmission elements. Due to the computational complexity of this MIP, implementation of OTS is limited. Therefore, different heuristics have been proposed to find good, sub-optimal solutions fast. The heuristics are often tested on small test cases with restricted analysis on actual systems. This work tests two of the recently developed fast heuristics on the Polish system to show their performance. The results suggest that the best solutions are among the top twenty candidates identified by the heuristics if they are based on the ACOPF solution. If the heuristics are calculated based on the DCOPF solution, the performance may be poor. The correlation between estimated benefits and actual benefits is not very promising in either of the cases.**

***Index Terms*—Optimal power flow, power system reliability, power transmission control, topology control**

NOMENCLATURE

Parameters:

b_k	Electrical susceptance of line *k*
c_g	Operation cost ($/MWh) of unit *g*
G	Set of generators, $g \in G$
$g(n)$	Set of generators connected to node *n*
g_k	Electrical conductance of line *k*
K	Set of all transmission elements, $k \in K$
N	Set of nodes, $n \in N$
$n(g)$	Node location of generator *g*
P_g^{max}	Maximum real power output of unit *g*
P_g^{min}	Minimum real power output of unit *g*
Q_g^{max}	Maximum reactive power output of unit *g*
Q_g^{min}	Minimum reactive power output of unit *g*
S_k^{max}	Capacity of transmission line *k* (MVA)
$\delta^+(n)$	Set of lines specified as to node *n*
$\delta^-(n)$	Set of lines specified as from node *n*

Variables:

d_{Pn}	Real power demand at bus *n*
d_{Qn}	Reactive power demand at bus *n*
P_g	Real power output of generator *g*
P_{kn}	Real power flow along line k at node *n*
Q_g	Reactive power output of generator *g*
Q_{kn}	Reactive power flow along line *k* at node *n*
S_{kn}	Complex power flow along line *k* at node *n*
V_n	Voltage magnitude at node *n*
θ_n	Voltage angle at node *n*
θ_{nm}	Voltage angle difference: θ_n-θ_m

Dual Variables:

λ_{Pn}	Real power LMP at node *n*
λ_{Qn}	Reactive power LMP at node *n*

I. INTRODUCTION

Traditionally, the transmission network is considered as a passive system and generation was optimized assuming a fixed transmission topology. The concept of dispatchable transmission was introduced in [1], which proposed a paradigm shift in the way the transmission topology is viewed. As a result, optimal transmission switching (OTS) was developed to harness the benefits of co-optimizing generation with transmission topology [2], [3]. Previous research shows that OTS would result in significant cost savings even under reliability constraints [4], [5]. Transmission switching has other applications, such as reliability improvement via corrective switching [6].

Binary variables representing the status of transmission lines make OTS a mixed-integer program (MIP). Real world power systems have thousands of transmission lines making the resulting OTS MIP a computationally expensive problem. Since the available computational time is limited, an MIP-based implementation of OTS in day-ahead and real-time procedures is not practical. An alternative to solving the full MIP is the use of switching heuristics to obtain a good, sub-optimal solution significantly faster. The MIP-heuristic introduced in [7] allows only one switching at a time, reducing

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the number of binary variables to one per iteration. This would significantly reduce the complexity of the problem. However, the formulation still requires mixed integer programming, which may still be too computationally challenging for certain applications that require fast solutions. There are other heuristics proposed in the literature, which only need the results of the original OPF. A DC-based heuristic is introduced in [8], [9] which ranks the lines based on their economic value. The line's value, or the congestion rent of a single line, is the price difference at the two ends of the line multiplied by the flow it carries [10]. The calculations are based on the results of a DCOPF. This will be referred to as the "DC heuristic". A similar heuristic is derived based on an ACOPF [11], which will be referred to as the "AC heuristic". In addition to the real power value of the line, the AC heuristic takes into account the reactive power and losses. The results obtained from the heuristics in small scale test cases show that they perform relatively well [10].

In this paper, these heuristics are tested to see if they perform well for a large-scale test case, the Polish system. The mathematical representations of the heuristics are presented briefly in the next section. The results suggest that the heuristics are not very different and the inclusion of losses and reactive power does not have a significant impact. This finding is in line with the conclusions made in [11], stating that the heuristics would be significantly different if the system was voltage constrained. The results also show that the best solutions are among the top twenty candidates identified by the heuristics. However, the correlation between the estimated and actual benefits from switching is not very strong.

The rest of this paper is organized as follows: section II includes the OPF formulation and a brief explanation of the heuristics' derivations. Section III presents the simulation of the heuristics on the Polish system followed by a discussion. Finally, section IV concludes the paper.

II. METHODOLOGY

In this paper, MATPOWER, a MATLAB based open sources power system simulation package, is used to solve the OPF problems [12], [13]. The detailed formulation and solution method for ACOPF and DCOPF problem is provided in [12]. Here, brief descriptions of AC as well as DCOPF formulations are presented. The ACOPF problem can be represented as shown in (1)-(11), with an objective function presented in (1). The AC line flow equations are provided in (2) and (3), and the node balance constraints for real and reactive power are represented by (4) and (5). Note that the dual variables for node balance constraints, λ_{Pn} and λ_{Qn}, represent the active and reactive power locational marginal prices. Constraints (6)-(11) represent the lower and upper bounds on variables.

$$\text{Min} \sum_G c_g P_g \tag{1}$$

subject to:

$$P_{kn} = -V_n V_m (g_k \cos(\theta_{nm}) + b_k \sin(\theta_{nm})) + g_k V_n^2 \tag{2}$$

$$Q_{kn} = V_n V_m (-g_k \sin(\theta_{nm}) + b_k \cos(\theta_{nm})) - b_k V_n^2 \tag{3}$$

$$-\sum_{k\in\delta^-(n)} P_{kn} + \sum_{g\in g(n)} P_g = d_{Pn} \tag{4}$$

$$-\sum_{k\in\delta^-(n)} Q_{kn} + \sum_{g\in g(n)} P_g = d_{Qn} \tag{5}$$

$$|S_{kn}| \le S_k^{max} \tag{6}$$

$$|S_{km}| \le S_k^{max} \tag{7}$$

$$P_g^{min} \le P_g \le P_g^{max} \tag{8}$$

$$Q_g^{min} \le Q_g \le Q_g^{max} \tag{9}$$

$$V_n^{min} \le V_n \le V_n^{max} \tag{10}$$

$$\theta_k^{min} \le \theta_n - \theta_m \le \theta_k^{max} \tag{11}$$

Using the ACOPF formulation presented, the sensitivity of the objective function to a marginal change in the status of a transmission line is calculated in [11]. This metric is used as a heuristic to estimate the benefits of switching the line. The heuristic is shown in (12),

$$LV_{AC} = P_{km}\lambda_{Pm} - P_{kn}\lambda_{Pn} + Q_{km}\lambda_{Qm} - Q_{kn}\lambda_{Qn}. \tag{12}$$

In this paper, we refer to the method that ranks lines based on (12) as the AC Heuristic. The metric represents the economic value of the line, which equals the revenue collected from the sale of power at the importing end minus the cost of buying power at the exporting end, considering losses and reactive power. AC heuristic considers the negative of the line value, suggesting that a line with a larger negative economic value is a potential switching candidate. It is not expected that the heuristic estimates match the actual benefits accurately, because the change in the status of the line is not marginal.

With the well-known assumptions of DC power flow, the ACOPF formulated in (1)-(11) can be simplified to a DCOPF, in which there is no reactive power or network losses. Moreover, the power flow constraint can be approximated by a linear equation presented in (13). Under this set of assumptions, and with linear cost functions, the DCOPF becomes a linear program (LP). Because of the special properties of LP, LP-based DCOPF can be solved much faster than the original ACOPF.

$$P_{kt} = b_k \theta_{nm} \tag{13}$$

The same sensitivity is calculated with the DC set of assumptions in [8], [9]. The metric estimating the DC benefits of the line is presented in (14). We refer to the method ranking lines based on this metric as the DC heuristic. The DC estimation of the line's value is the same as the AC estimation, ignoring the reactive power and losses. It is concluded in [11] that the two heuristics may produce significantly different results if the system is voltage constrained.

$$LV_{DC} = P_k(\lambda_{Pm} - \lambda_{Pn}) \tag{14}$$

III. SIMULATION STUDIES

We test the two heuristics on the Polish test case provided by MATPOWER. The system has 2383 nodes, 327 generators, and 2896 transmission lines. We assume that all of the generators are on. The cost functions included in the dataset are linear, which matches the formulation presented in the previous section. In order to study the performance of the heuristics, we compare the actual benefit from the proposed switching action with the estimated benefit calculated by the heuristics. The actual switching benefit is the total cost difference between the case in which the transmission line is in the system, and the case in which it is taken out. We simulate the performance of the heuristics under three different settings:

1. DC Heuristic with DCOPF: a DCOPF is performed and all the primal and dual variables are taken from the DCOPF solution. The actual benefits are calculated through the total cost comparison of the two DCOPFs. The switching benefits are also estimated through the DC heuristic introduced in (14). A comparison between the actual and estimated benefits provides information on the performance of the DC heuristic with a DCOPF. Note that the solution to a DCOPF may or may not be AC feasible.

2. DC Heuristic with ACOPF: the dual and primal variables as well as the actual benefits are calculated through an ACOPF. The estimated switching benefits are obtained from the DC heuristic, which does not include losses or reactive power. Note that under this setting, despite using the DC heuristic, the power flow and active power LMP come from an ACOPF. A comparison between the actual and estimated benefits provides information on the performance of the DC heuristic with an ACOPF.

3. AC Heuristic with ACOPF: the dual and primal variables are specified through an ACOPF algorithm. The actual switching benefits are also calculated by comparing the total cost obtained from the two ACOPFs. Under this setting, the benefits are estimated through the AC heuristic presented in (12). A comparison between the actual and estimated benefits provides information on the performance of the AC heuristic with an ACOPF.

Figure 1 compares the benefits obtained by a single switching action with the estimated benefits calculated by the DC heuristic under setting 1. Figure 2 shows the performance of an algorithm based on the DC heuristic using a DCOPF for the first twenty switching candidates. The dashed line specifies the maximum possible benefit from the switching identified by an ACOPF while the dotted line shows the maximum possible benefits of switching using a DCOPF. The results show that the algorithm is not able to find the best switching action in the first twenty candidates it proposes. Five out of twenty proposed candidates are beneficial actions when tested with a DCOPF. However, there exist only two candidates that provide ACOPF beneficial switching actions. In electricity markets today, all the procedures are based on DCOPF due to the computational complexity of ACOPF. However, operators need to make sure that the solution is AC feasible. This is often done via out of market correction (OMC) mechanisms [14]. Our results suggest that switching candidates identified by the solution of a DCOPF may not be AC feasible or may not be beneficial even though DCOPF identifies them to be beneficial.

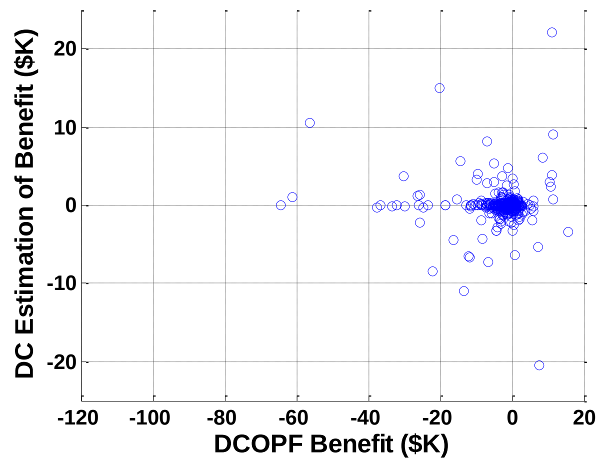

Figure 1. The benefits identified by DCOPF versus the DC heuristic estimation of the benefits using DCOPF.

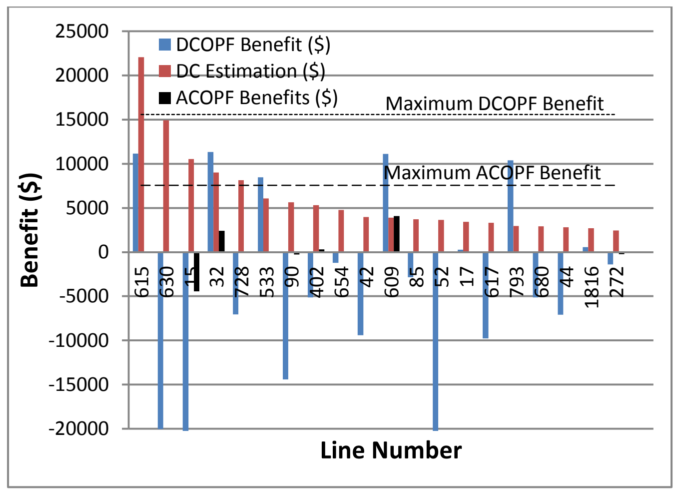

Figure 2. Performance of the DC heuristic for the first twenty lines identified by the heuristic using DCOPF. The dotted line shows the maximum possible DCOPF benefit while the dashed line represents the maximum possible ACOPF benefit.

Figures 3 and 4 show the same results under setting 2 where ACOPF is used instead of DCOPF. The results suggest that the algorithm is able to identify the best switching action among its first twenty proposed candidates. Six out of twenty proposed actions are beneficial. Note that the only difference between settings 1 and 2 is the fact that ACOPF solution is used under setting 2 for both actual and estimated benefit calculation. However, under both settings the DC heuristic presented in (14) is employed. The difference between the results comes from the fact that the dispatch and prices are different when AC power flow constraints are taken into account in the optimal power flow problem.

Figures 5 and 6 show the results under setting 3 where the AC heuristic is used with ACOPF solution. The results are very similar to those of setting 2 with six beneficial solutions among the first twenty proposed actions.

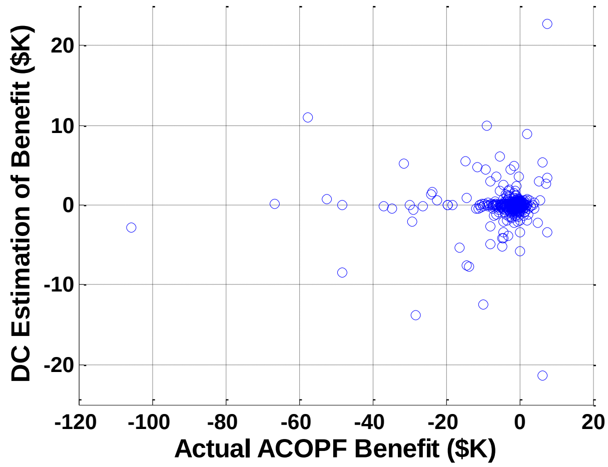

Figure. 3. The actual benefits obtained by ACOPF versus the DC heuristic estimation of the benefits using ACOPF.

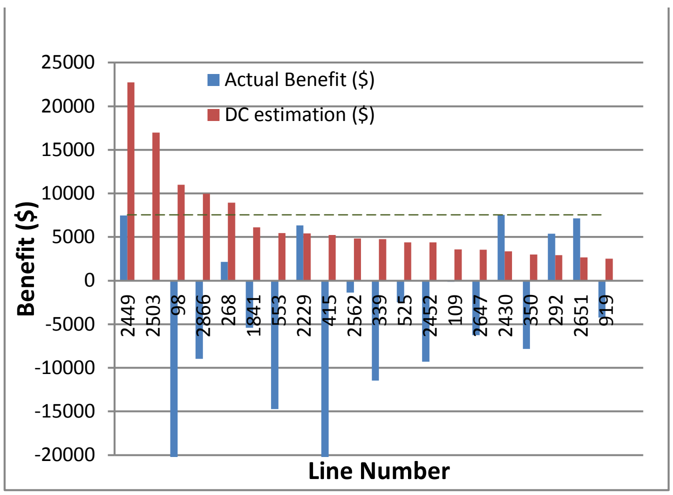

Figure 4. Performance of the DC heuristic for the first twenty lines identified by the heuristic using ACOPF. The dashed line shows the maximum possible benefit.

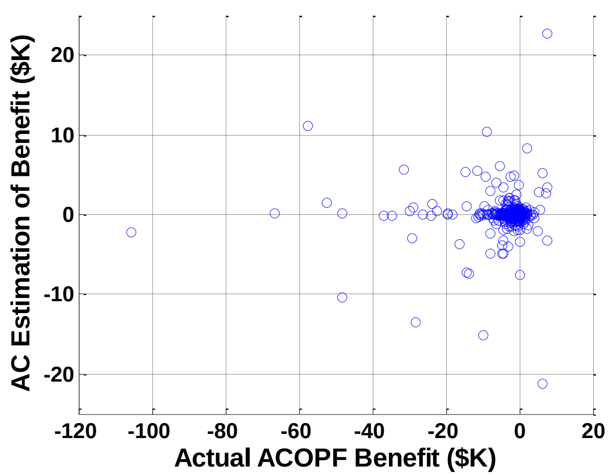

Figure 5. The actual benefits obtained by ACOPF versus the AC heuristic estimation of the benefits using ACOPF.

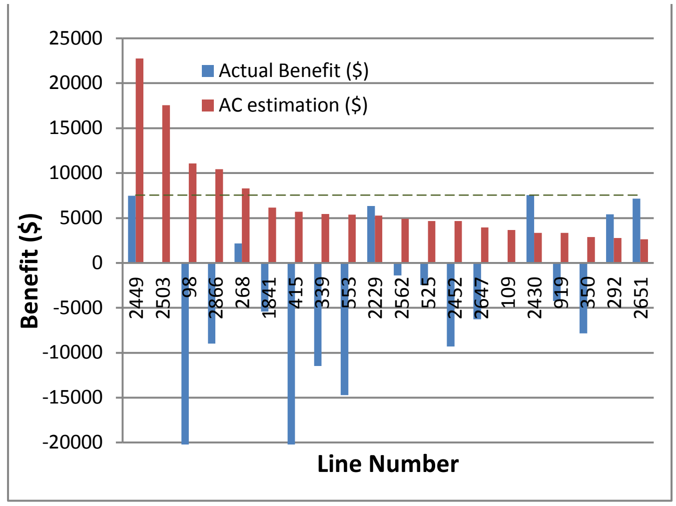

Figure 6. Performance of the AC heuristic for the first twenty lines identified by the heuristic using ACOPF. The dashed line shows the maximum possible benefit.

The results obtained under settings 2 and 3 show that AC and DC heuristics produce very similar results when the ACOPF solution is used. Under both settings, six out of twenty proposed actions were beneficial and the algorithm was able to identify the best switching action. The only difference was a slight change in the candidates' order. Such results were expected and are in line with the conclusions of [11], which suggests the results to be similar when the system is not heavily voltage constrained. Nevertheless, the results obtained under setting 1, where the DCOPF solution is used for heuristic calculations, are substantially different from those of settings 2 or 3. The difference appears both in the suggested switching candidates and the benefits.

As was stated before, in electricity markets today, ACOPF solutions are not generally available– similar to setting 1. Our results show that the studied heuristics do not provide consistent results when they are based on the DCOPF solution compared to a more realistic ACOPF. The more realistic benefits, ACOPF based benefits, as well as the proposed candidates are different than those based on a DCOPF.

With the applications of high performance computing, a batch of parallel processors can be used to identify the actual benefits of the proposed candidates [15]. Here, we show how using multiple processors would impact the performance of such algorithms. We compare the benefits obtained by the best candidate in the batch with the average estimated benefit identified by the heuristic. For this part, we only use the AC heuristic with ACOPF, similar to the conditions of setting 3. Figures 7, 8, and 9 show the comparison for the batch sizes of 10, 50, and 100 respectively. The results show that, by having a batch size of greater than 50, the algorithm was able to find at least one switching candidate within each batch that improved the objective function. However, even with a large batch size, there exist beneficial solutions within the batches that have negative expected benefit. These solutions correspond to the points in the fourth quadrant of Figures 3 and 5. The implication of this finding is that some lines with large congestion rents may be good switching candidates.

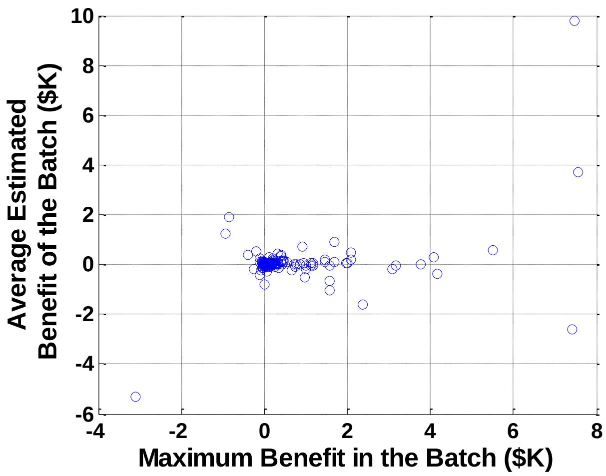

Figure 7. Maximum benefits for each batch of processors versus the average benefits identified by the AC heuristic. Each batch contains 10 CPUs.

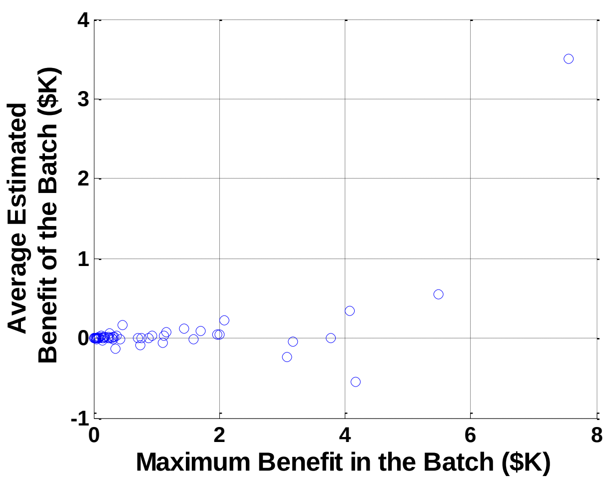

Figure 8. Maximum benefits for each batch of processors versus the average benefits identified by the AC heuristic. Each batch contains 50 CPUs.

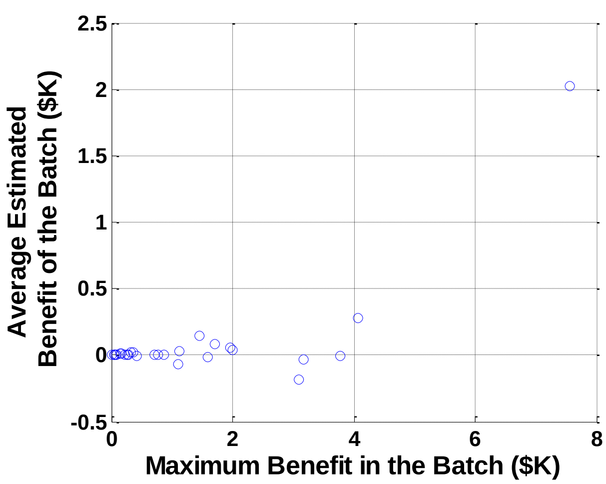

Figure 9. Maximum benefits for each batch of processors versus the average benefits identified by the AC heuristic. Each batch contains 100 CPUs.

IV. CONCLUSIONS

Due to the computational complexity of the OTS problem, different heuristics are used to obtain fast sub-optimal solutions. The heuristics are often tested on small scale systems and the scalability of their application is not well understood. We studied the performance of two such fast heuristics on the Polish system. The heuristics were studied under three different settings: DC heuristic with DCOPF, DC heuristic with ACOPF, and AC heuristic with ACOPF. Our results suggest that the AC and DC heuristics are not very different when they are based on the solution to ACOPF. However, the heuristics do produce different results if they are based on DCOPF solutions. Our results suggest that DCOPF based solutions obtained for OTS may not perform well under realistic system conditions modeled by an ACOPF. Since the market procedures are based on DCOPF, not ACOPF, and AC feasibility is achieved via OMC routines, implementation of ACOPF based heuristics would not be straightforward.

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