Optimal Coordinated Operation of Distributed Static Series Compensators for Wide-area Network Congestion Relief

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***Abstract*—Relieving network congestions is a critical goal for the safe and flexible operation of modern power systems, especially in the presence of intermittent renewables or distributed generation. This paper deals with the real-time coordinated operation of distributed static series compensators (DSSCs) to remove network congestions by suitable modifications of the branch reactance. Several objective functions are considered and discussed to minimize the number of the devices involved in the control actions, the total losses or the total reactive power exchanged, leading to a non-convex mixed-integer non-linear programming problem. Then, a heuristic methodology combining the solution of a regular NLP with *k*-means clustering algorithm is proposed to get rid of the binary variables, in an attempt to reduce the computational cost. The proposed coordinated operation strategy of the DSSCs is tested on several benchmark systems, providing feasible and sufficiently optimal solutions in a reasonable time frame for practical systems.**

***Index Terms*—Distributed static series compensation (DSSC), flexible AC transmission system (FACTS), mixed-integer nonlinear programming (MINLP), wide-area network control.**

I. Introduction

THE electricity sector is quickly shifting towards low-fossil electricity generation constituted primarily by intermittent renewable energy sources. Despite their advantages in achieving the objectives like emission reduction, they give rise to the problems associated with their low dispatching capability and unanticipated power grid congestions. In this upcoming context, additional flexibility resources will be required to properly solve these new problems. As a matter of fact, new operational schemes involving self-generation, electric vehicles with smart charging/discharging, domestic- and utility-scale energy storage, smart grid technologies, microgrids, etc. are being applied currently in modern power systems [1]. This revolution, however, is not just focused at the distribution and end user levels. The safe operation of power grids with more uncertain power flows requires also improvements at the transmission level. In this regard, flexible AC transmission systems (FACTSs) have proven to be an attractive choice for improving the network controllability, owing to their ability to rapidly and continuously varying electrical magnitudes (voltages, currents, impedances, etc.) without resorting to any electromechanical component [2]-[5]. In general, the more controllability these fast-acting transmission assets provided, the more congestions can be relieved without having to resort to other short-term alternatives that increase the system operating costs, e.g., topological maneuvers, conventional generation redispatch [6] or renewable generation curtailments [7]. In addition, it is worth noting that FACTSs can be installed in existing substations, making them an attractive option compared with the construction of new transmission corridors, which is almost impossible due to environmental constraints or social objections. Moreover, the new breed of recently proposed distributed FACTSs (not to be confused with distribution-level FACTSs) makes the investment on this kind of assets even more attractive compared with the traditional ones. Quick installation, modular upgrading, small space, flexibility or the possibility of being transferred from one location to another are some of the distinguishing features [8], [9] with respect to conventional FACTSs. Recently, it has been suggested that they could be even used in moving target defense (MTD) strategies, which aim at detecting and preventing the effects of false data injection attacks [10].

Within this category of distributed FACTSs, static series synchronous compensators (SSSCs) stand out, frequently attached directly to substation bays through single-turn transformers [11], [12] or even with transformer-less solutions, called distributed static series compensators (DSSCs) [13]. Those devices insert a series voltage at the fundamental frequency mainly with the purpose of re-routing loop power flows. DSSCs present several advantages with respect to previous series compensation based on mechanical or thyristor

Manuscript received: February 25, 2021; revised: July 14, 2021; accepted: September 10, 2021. Date of CrossCheck: September 10, 2021. Date of online publication: October 29, 2021.

This work was supported by the Spanish Ministry of Economy and Competitiveness (No. ENE2017-84813-R), the CERVERA research program of the Spanish Industrial and Technological Development Centre (CDTI) under the research project HySGrid + (CER-20191019), and Junta de Andalucía (No. P18-TP-3655).

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DOI: 10.35833/MPCE.2021.000265

switches [3]. A complete literature survey of series compensation in power systems is presented in [14], where a comprehensive review and a comparison between the different series compensation technologies are performed, highlighting the benefits of the distributed devices.

This extensive review of the state of the art reveals two major research areas on DSSCs: planning and operational applications. The planning tries to determine the optimal DSSC deployment (e.g., number, rating, and location) given a limited budget and a series of future planning scenarios. This usually leads to a least-cost problem, where the resulting DSSC investment is compared with alternative reinforcement techniques [15]-[17], or a compromise solution between investment and system loadability enhancement is targeted [18]. Conversely, the operational problems are devoted to determining the real-time settings of a set of already installed DSSCs so that the network operating state is somehow optimized. In this case, a diversity of goals suited for steady-state or dynamic conditions [14], [19] can be applied.

Several previous works have been published dealing with the inclusion of series FACTS models into optimal power flow (OPF) tools [20], [21]. In [22], a thorough AC-OPF model is presented considering distributed FACTS devices as control variables, and an interior-point solver is used. A comprehensive review of the existing techniques to solve the resulting optimization problem can be found in [23] and [24], where different methodologies ranging from conventional Newton's methods to genetic algorithms have been applied. Besides providing nearly optimal solutions, those methods are required to be computationally efficient and amenable for real-time applications [25], [26]. Also, the choice of the objective function depends on whether the resulting control actions are to be implemented automatically or manually, i.e., operator-assisted. In the latter case, as explained in [27], the number of control actions should be as small as possible, while intermediate states should remain feasible, for which gradient-descent techniques are most suitable.

This paper deals with the role that DSSCs may play in improving the operation security of transmission systems, through corrective control actions aimed at relieving network congestions in real time. This customarily leads to a non-linear programming (NLP) problem. However, when considering the discrete nature of the control devices, the resulting model generalizes to a mixed-integer non-linear programming (MINLP) problem, which involves binary variables. Solving MINLPs for large systems is time-consuming, usually leading to unacceptable delays when real-time corrective actions are sought. Therefore, a hybrid methodology is proposed, aimed at handling binary variables in a more efficient fashion, iteratively combining NLP with heuristic clustering algorithms.

The remainder of this paper is organized as follows. First, the general framework defining the scope and goals of this study is described. Second, the mathematical models involved in the optimization of the DSSC operation for congestion relief are presented, followed by a description of the possible objective functions that can be considered by the OPF problem. Next, a heuristic methodology combining the solution of a regular NLP with clustering algorithms is proposed. Different test cases involving the IEEE 14-bus, 118-bus, and 300-bus test systems are considered to evidence the performance of the proposed methodology. Finally, the main conclusions and future research efforts are outlined.

II. DSSC Operation Framework

Unlike shunt FACTSs, whose influence on the grid is generally limited to nearby buses, and hence whose settings can be determined based mainly on locally measured magnitudes, series FACTSs, including DSSCs, usually have a more widespread impact on meshed transmission systems. Therefore, the setpoints of their local control systems should be ideally defined through a centralized wide-area controller, capable of considering all network interactions and constraints. Evidently, this presumes the existence of a wide-area communication infrastructure, which is an off-the-shelf technology in modern transmission systems, capable of exchanging the information in real time between different geographical locations. Note that such information and communication technology (ICT) infrastructure is becoming more and more common to support emerging power grid applications, including but not limited to phasor measurement unit (PMU) based situational awareness [28], advanced supervisory control and data acquisition (SCADA) functions [29], online decision-making for renewable energy penetration (security assessment) [30], dynamic line rating (DLR) applications [31], isolating faults (protection), power restoration, load shedding, demand response, and in particular, FACTS coordination [32].

Therefore, the setpoints of the distributed controllers can be computed in real time in the energy management system (EMS) following the flowchart of Fig. 1.

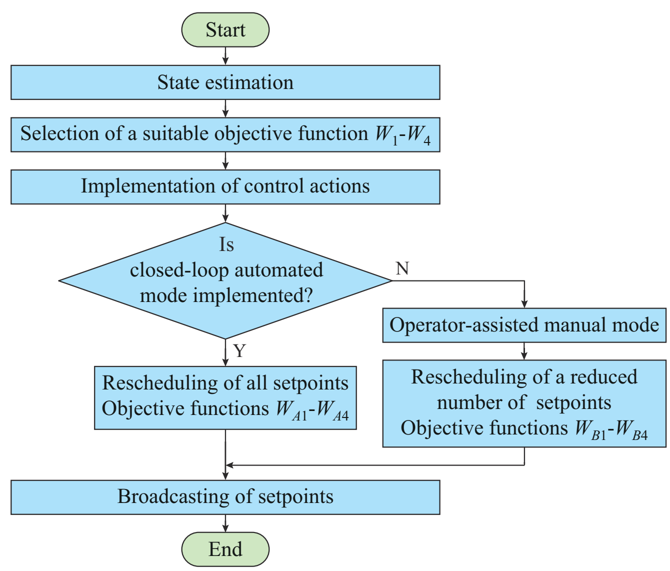

Fig. 1. Basic flowchart of real-time operation of transmission system.

First, the state estimator determines the most likely network state considering the raw measurements from the field. Then, depending on whether all the electrical magnitudes are within their recommended limits or not, the most suitable objective function is chosen. In absence of network congestions, the operator may decide, for instance, to reduce power losses, or maximize the reactive power reserve of generators.

Note that, in deregulated systems, where the generation is open to competition, the active power of generators is imposed by the outcome of an auction process which cannot be modified unless strictly necessary. Therefore, customarily, only reactive power controllers such as capacitor banks or on-load tap changers are involved in the optimization process. However, the presence of DSSC will allow branch series impedances to be modified to a certain extent, which in turn may prevent branch congestions without having to reschedule the active power of generators.

When selecting the objective function, it should be kept in mind whether the control actions are supervised, approved, and then performed manually by an operator [27], or they are automatically implemented, i. e., in closed-loop mode [33]. In the former case, the human operator will be burdened if the number of control actions to be implemented on a regular basis is excessive. Therefore, it is advisable to adopt an objective function that somehow minimizes the number of control actions, provided the constraint violations are eliminated.

III. Mathematical Model for DSSC Operation

This section formulates the mathematical programming problem with a complete steady-state power flow model of DSSC. Working with a full AC model is particularly important in this case, since branch loadings may be significantly affected by reactive power flows. In this sense, the network model adopted in this paper generalizes the one elaborated in [15], which neglects the power system losses, by duly considering both the network resistances and the effect of the DSSC devices on the $\boldsymbol{y}_{bus}$ elements, some of which become control variables.

A. Steady-state Power Flow Model of DSSC

Each DSSC device installed in the network is represented as a variable reactance w_{km} (the internal resistance is neglected) inserted in series between nodes k and m. Accordingly, w_{km} changes the real and imaginary components of the branch (transmission line or power transformer line) series admittance, which become variables as:

$$g_{com,km}=\frac{R_{km}}{R_{km}^2+\left(X_{km}+u_{km}w_{km}\right)^2} \tag{1}$$

$$b_{com,km}=-\frac{X_{km}+u_{km}w_{km}}{R_{km}^2+\left(X_{km}+u_{km}w_{km}\right)^2} \tag{2}$$

$$u_{km}\in\{0,1\} \tag{3}$$

where R_{km} is the series resistance of the branch between nodes k and m; X_{km} is the original reactance of the branch; and u_{km} is an auxiliary binary variable introduced for convenience to define whether the DSSC is actually regulating the series reactance ($u_{km}=1$) or bypassed ($u_{km}=0$). Note that the use of the binary variables u_{km} is of interest in operator-assisted control modes, where minimizing the number of control actions is always a key aspect, as discussed in Section IV. The branch variable admittances are used to build the real and imaginary components of the bus admittance matrix ($\boldsymbol{y}_{bus}=\boldsymbol{g}+\mathrm{j}\boldsymbol{b}$), whose elements g_{km} and b_{km} are defined as:

$$g_{km}=\begin{cases} G_{SH,k}+\sum\limits_{i=1}^{N} g_{com,ki} & k=m \\ -g_{com,km} & k\neq m \end{cases} \tag{4}$$

$$b_{km}=\begin{cases} B_{SH,k}+\sum\limits_{i=1}^{N}\left(b_{com,ki}+\dfrac{B_{line,ki}}{2}\right) & k=m \\ -b_{com,km} & k\neq m \end{cases} \tag{5}$$

where $G_{SH,k}$ and $B_{SH,k}$ are the parameters that correspond to the real and imaginary components of the shunt admittances connected to node k, respectively; N is the number of nodes; and $B_{line,ki}$ is the capacitive susceptance of transmission line ki (0 for transformer branches). Transformer taps are not considered.

B. Optimization Model for DSSC Coordinated Operation

The problem addressed in this paper consists of minimizing the "effort" or "cost" of jointly rescheduling a subset of DSSC (where the "effort" is measured in different ways, as presented below), so that the power system is operated within security constraints, that is, in a normal state lacking network congestions, i. e., overload, under-voltage or over-voltage. Mathematically, the model is formulated as the objective function (6) subject to the set of constraints (7) to (15).

$$\min W_x \tag{6}$$

s.t.

$$P_{Gk}-P_{Lk}=v_k\sum_{j=1}^{N}v_j\left(g_{kj}\cos\left(\theta_k-\theta_j\right)-b_{kj}\sin\left(\theta_k-\theta_j\right)\right) \tag{7}$$

$$q_{Gk}-Q_{Lk}=v_k\sum_{j=1}^{N}v_j\left(g_{kj}\sin\left(\theta_k-\theta_j\right)-b_{kj}\cos\left(\theta_k-\theta_j\right)\right) \tag{8}$$

$$p_{G1}-P_{L1}=V_1\sum_{j=1}^{N}v_j\left(g_{1j}\cos\left(\theta_1-\theta_j\right)-b_{1j}\sin\left(\theta_1-\theta_j\right)\right) \tag{9}$$

$$p_{km}=v_k v_m\left(g_{km}\cos\left(\theta_k-\theta_m\right)-b_{km}\sin\left(\theta_k-\theta_m\right)\right) \tag{10}$$

$$q_{km}=v_k v_m\left(g_{km}\sin\left(\theta_k-\theta_m\right)-b_{km}\cos\left(\theta_k-\theta_m\right)\right) \tag{11}$$

$$-A_1X_{km}\le w_{km}\le A_2X_{km} \tag{12}$$

$$Q_{Gk,\min}\le q_{Gk}\le Q_{Gk,\max} \tag{13}$$

$$V_{k,\min}\le v_k\le V_{k,\max} \tag{14}$$

$$i_{km}^2=\frac{p_{km}^2+q_{km}^2}{v_k^2}\le I_{km,\max}^2 \tag{15}$$

where P_{Gk} is the active power generation at bus k other than the slack bus; P_{Lk} is the active power load at bus k other than the slack bus; q_{Gk} is the reactive power generation at bus k (including the slack bus); $Q_{Gk,\min}$ and $Q_{Gk,\max}$ are the minimum and maximum reactive power generations, respectively; v_k is the voltage magnitude of bus k, and for voltage regulated buses, v_k is a parameter, i. e., $v_k=V_k$; $V_{k,\min}$ and $V_{k,\max}$ are the minimum and maximum voltage magnitudes, respectively; Q_{Lk} is the reactive power load at bus k (including the slack bus); p_{G1} is the active power generation of the slack bus, labelled as bus 1, whose voltage angle $\theta_1 = 0$ is used as reference; P_{L1} is the active power load of the slack bus; θ_j, θ_k, and θ_m are the voltage angles of nodes j, k, and m, respectively; A_1 and A_2 are the real numbers representing the allowed capacitive and inductive sizes of DSSCs, respectively, as a (or multiple) fraction of the original branch series reactance; i_{km} is the current of the branch between nodes k and m; $I_{km,\max}$ is the specified ampacity of the branch between nodes k and m; and p_{km} and q_{km} are the active and reactive power flowing through the branch between nodes k and m, respectively.

Constraints (7)-(9) ensure the fulfillment of the AC power flow equations, including series compensated branches, while (10) and (11) relate branch power flows with the state variables. Constraints (12)-(15) impose limits on state, control and dependent variables, among which the ampacity and voltage constraints (14) and (15) are the most important for the optimization model considered in this work. Indeed, even if series compensation is the most influential on branch power flows, its impact on bus voltages is not negligible either, particularly for heavily loaded systems and/or long-distance corridors. The goal is to optimally operate the set of existing DSSCs so that branch currents and voltage magnitudes are kept within acceptable limits, which cannot be assured when using DC power flow models.

The above optimization problem is a complex and highly non-linear and non-convex one, irrespective of the objective function to minimize. Note that (7)-(9) involve the product of up to four variables, i.e., voltage magnitudes of the two terminal buses, controllable series admittance (in turn embedding products of the form $u_{km}w_{km}$), and cosine or sine of bus phase angles. Therefore, several feasible local minima are expected in the general case.

IV. Suitability of Objective Functions

The candidate objective functions considered in this work are summarized in Table I. Those objective functions have been divided into two groups, W_A and W_B, depending on whether the control actions are to be supervised and executed manually by an operator, and hence the number of control actions is an issue. Different options within each group are considered, so that the transmission operator can make a choice of the objective function that better suits its demands, as discussed in the sequel. Note that, irrespective of the objective function chosen, the resulting state should satisfy the set of constraints (12)-(15).

The objective functions in group W_A usually involve all control variables, and hence are more suitable when the network state is optimized in the closed-loop automated mode [33], particularly when many network congestions arise or the operator simply wishes to improve the voltage profile. This closed-loop automated mode, although technically feasible, is not still commonly found in EMS, but will eventually be trusted by more and more network operators. The operator may be interested in reducing the total power system losses, for which W_{A1} should be used. If the goal is rather to minimize the wear and tear of DSSC devices, which in turn reduces the maintenance costs and extends their service life, then the objective function could be W_{A2} or W_{A3} (sum of series reactances inserted by the DSSC), depending on whether the 1-norm or 2-norm is preferred. Related to this goal, the total reactive power injected/absorbed by all the DSSCs can also be considered (W_{A4}). All these objective functions lack binary variables, hence leading to NLPs.

TABLE I
Objective Functions

Control action	$W_x = \sum_{\forall km} f$	f	Definition of $\sum_{\forall km} f$
Closed-loop automated mode	W_{A1}	$g_{com,km}(v_k^2 + v_m^2 - 2v_k v_m \cos\theta_{km})$	Total branch losses
	W_{A2}	$\lvert w_{km} \rvert$	Total DSSC reactance (1-norm)
	W_{A3}	w_{km}^2	Total DSSC reactance (2-norm)
	W_{A4}	$i_{km}^2 \lvert w_{km} \rvert$	Total reactive power absorbed or supplied by DSSCs
Operator-assisted manual mode	W_{B1}	u_{km}	Total number of operating DSSCs
	W_{B2}	$u_{km} \lvert w_{km} \rvert$	Total reactance of operating DSSCs (1-norm)
	W_{B3}	$u_{km} w_{km}^2$	Total reactance of operating DSSCs (2-norm)
	W_{B4}	$u_{km} i_{km}^2 \lvert w_{km} \rvert$	Total reactive power absorbed or supplied by operating DSSCs

Conversely, objective functions within group W_B are especially suited when human intervention is involved, typically when a few network congestions occur, where corrective actions are required to return to a normal state. In this case, the goal is twofold. On the one hand, given that the corrective control actions are supervised by a human network operator, the number of control actions should be reduced as much as possible to facilitate the decision-making. On the other hand, returning to the normal state must be as fast as possible. Unfortunately, these two goals are frequently contradictory.

The minimization of the number of control actions can be achieved by introducing in the objective function the binary variables u_{km}, related to each installed DSSC. In this way, W_{B1} minimizes the number of DSSCs whose setpoint should be updated to relieve the network congestions. Following this line, the objective functions W_{B2} to W_{B4} are derived from the corresponding ones in group W_A, by introducing the corresponding binary variables. These objective functions can be of interest because they minimize the use of the existing DSSCs and, therefore, maximize the resource "reserves" to face new congestions in the short term, without resorting to generation dispatch or renewable generation curtailments.

The introduction of the binary variables, however, turns the problem into an MINLP whose solution is time-consuming. Moreover, those problems may have multiple locally optimal solutions and can take a while just to identify whether a solution actually exists or if the solution is globally optimal [34]. In these cases, heuristic techniques may be a good compromise solution to limit the search space if a practicable and efficient algorithm for real-time elimination of network congestions is targeted.

The next section outlines the application of a heuristic methodology capable of eliminating identified network congestions by means of DSSC, where clustering techniques are applied to reduce as much as possible the computational cost of determining a minimum subset of corrective actions.

V. Heuristic Methodology Combining Solution of Regular NLP with Clustering Algorithm

The aim of the proposed heuristic methodology is to somehow get rid of the binary variables u_{km} involved in the objective functions W_B, which turns the problem into an MINLP, while at the same time dealing with the high number of control actions typically arising when the objective functions W_A are considered. The proposed methodology is based on the sequential procedure outlined in Fig. 2. First, an NLP using any of the objective functions in group W_A is solved. Then, a k-means clustering algorithm is applied to classify the resulting compensation settings into clusters according to their relative values. The DSSCs with the lowest compensation setpoints are discarded while those with the higher ones are selected for a new NLP optimization. The procedure is repeated until the NLP solver provides sufficiently close results in two consecutive runs. When this happens, the computed control actions are applied in the DSSCs.

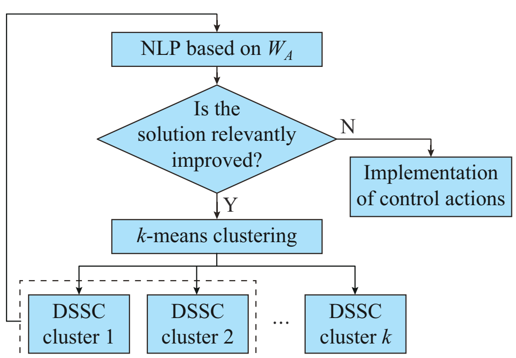

Fig. 2. Sequential procedure for reducing computational cost of corrective actions.

The k-means clustering algorithm tries to partition the dataset into k pre-defined non-overlapping clusters, with each data point belonging to only one cluster. The applications of k-means clustering algorithm are extensive, particularly for power grid planning problems such as pattern definition preserving the original information of complex systems [35], [36], mixed heuristic optimization [37]-[39] or uncertainty modeling [40]. Two clustering algorithms are proposed with different numbers of resulting clusters.

1) Algorithm $k3$. In the first algorithm, as illustrated in Fig. 3(a), reactance values obtained from the first run of the NLP are grouped into 3 sets, using 3-means clustering. Then, the elements in cluster 3 (low values) are forced to be zero (no longer eligible) while the elements in clusters 2 (middle values) and 1 (large values) are retained for the next run. In this way, DSSCs with reactance values which are neither too small nor high enough (group 2) have a second chance to be operated.

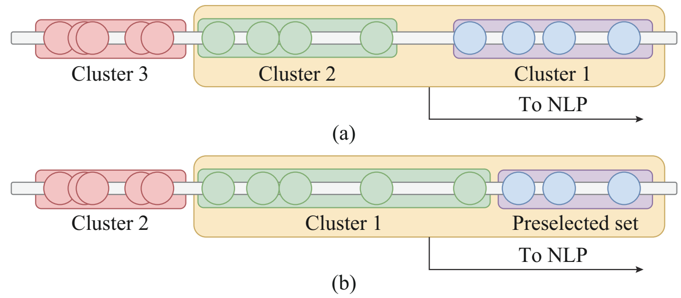

Fig. 3. Two clustering algorithms. (a) Algorithm $k3$ (3-means clustering). (b) Algorithm $k2$ (preselected set and 2-means clustering).

2) Algorithm $k2$. In the second algorithm, as illustrated in Fig. 3(b), the series reactance provided by the first run of the NLP is first ranked according to its absolute values. Then, a subset of M DSSCs with the highest settings is preselected, where M corresponds to the number of constraint violations to be solved. The remaining DSSCs are split into two groups by 2-means clustering, and the subset with lower reactance values (cluster 2) is discarded, while the subset with higher values is added to cluster 1 for a subsequent run of the NLP.

VI. Case Studies

The IEEE 14-bus, 118-bus, and 300-bus test systems are used to evaluate the performance of the proposed methodology for relieving the network congestions, when the objective functions outlined in Table I are adopted.

The IEEE 14-bus test system [41] comprises 14 buses, 17 transmission lines, three 220 kV/132 kV transformers (taps at nominal position), two generators, and three synchronous condensers. Generator 2 is considered as a PQ generator, i.e., its voltage is not regulated, and the synchronous condensers are assumed to be unavailable. It is assumed that every branch contains a DSSC, i.e., excluding the tertiary winding, a total of 19 devices. The IEEE 118-bus test system [42] comprises 177 transmission lines, 28 transformers (taps at nominal position), and 19 generators. As in the IEEE 14-bus case, it is assumed that a DSSC is located at all branches (excluding tertiary windings). Finally, the IEEE 300-bus test system [43] contains 69 generators, 60 transformers (taps at nominal position), 304 transmission lines, and 195 loads. Again, a DSSC is assumed in each transmission line. Note that, as these IEEE test systems do not consider branch thermal limits, customized values for the maximum allowable ampacity are adopted for each branch, depending on its rated voltage. Parameters $V_{k,\min}$ and $V_{k,\max}$ are defined as 0.9 and 1.1 p.u., respectively, according to operational limits typically imposed by grid codes.

Regarding the DSSC ratings, the manufacturer can arrange the device according to the customers' needs. In our experiments, parameters A_1 and A_2 are defined as -0.9 and 1, respectively, for all branches, so capacitive (inductive) compensation can reach up to 90% (100%) of the series reactance (in practice, the inductive range could be higher than 100%).

It has been considered that the DSSC setpoints are zero in the base case, i.e., all DSSCs are considered in bypass mode by default.

The resulting model has been coded in AMPL® (an algebraic modeling language for optimization) [44], and solved by resorting to the KNITRO® solver [45] with no execution time limit and stopping the process if a feasible solution is not found after 10000 iterations. MATLAB® scripts are used to support and coordinate the whole process (reading network data, calling AMPL, processing results, etc.). The software has been tested using a 1.8 GHz, i7-8550U processor with four cores and 16 GB of RAM. The results have been validated in DIgSILENT PowerFactory®.

The following subsections will analyze the performance of the different objective functions outlined in Table I, highlighting the high computational time required for solving the MINLPs. This motivates the use of the proposed methodology whose performance is analyzed subsequently.

A. Performance of Proposed Objective Functions

This subsection analyzes the results obtained for the IEEE 14-bus and 118-bus test systems.

1) IEEE 14-bus Test System

In this case shown in Fig. 4(a), three overloads are present (lines 1-2, 4-5, and 6-13), but the load of line 2-4 is also very close to its limit. These congestions are relieved by means of four DSSCs installed in the lines depicted in Fig. 4(b).

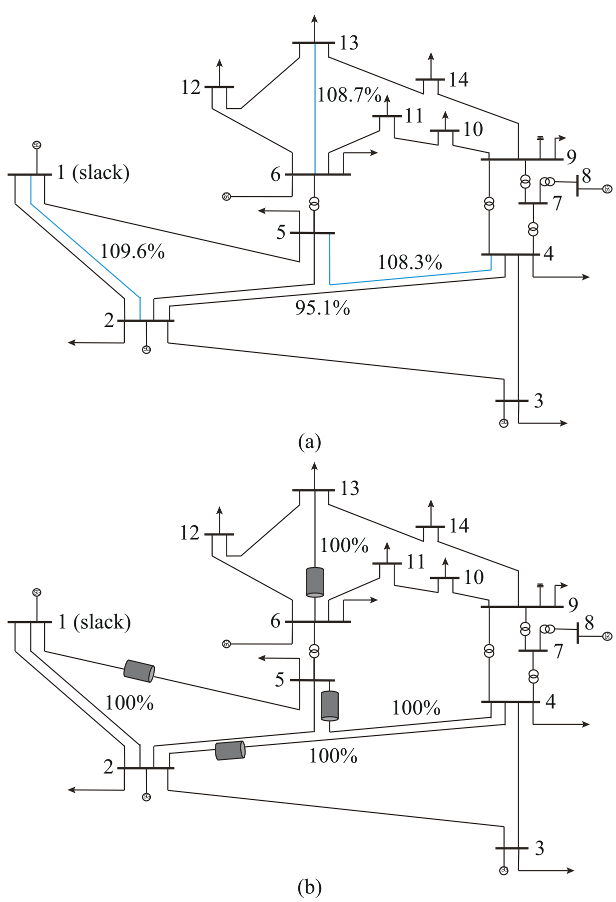

Fig. 4. IEEE 14-bus test system with 3 line congestions and resulting state when using W_{B2}. (a) Test system. (b) Resulting state when using W_{B2}.

The obtained results evidence the usual characteristics of the proposed objective functions. Regarding the NLPs (objective functions W_A), note that W_{A1} minimizes the whole system losses, but this is achieved by activating very high values of series reactance, which is not an advisable solution if the useful life of the DSSCs is to be maximized. Conversely, the objective function W_{A4} gets the lowest reactive power but uses all the available DSSCs to solve the congestion problems. The objective function W_{A2} (1-norm) calls for a lower number of involved DSSCs than W_{A3} (2-norm). It is well-known that quadratic functions tend to reschedule all control variables, most of them by modest amounts (in this case, the reactance is very small), at a moderate computational cost, as shown in Table II.

TABLE II
OPERATION RESULTS OF DSSCS CONSIDERING DIFFERENT OBJECTIVE FUNCTIONS IN IEEE 14-BUS TEST SYSTEM WITH 3 LINE CONGESTIONS

Function	Number of DSSCs	Total reactance (p.u.)	Loss (MW)	Reactive power of DSSC (Mvar)	Computational time (s)
	0	0.0000	14.35	0.0	0.03
W_{A1}	19	2.3632	13.64	33.8	0.03
W_{A2}	12	0.3018	13.97	14.3	0.36
W_{A3}	19	0.2854	14.29	10.5	0.05
W_{A4}	19	0.7702	14.31	4.8	0.38
W_{B1}	3	0.3076	14.52	20.1	0.41
W_{B2}	4	0.2097	14.22	7.2	18.34
W_{B3}	19	0.2854	14.30	10.5	0.05
W_{B4}	9	0.7982	14.31	3.4	30.20

Regarding the MINLPs, W_{B2} obtains the lowest total reactance at a significant computational effort. Whereas W_{B1} results in the lowest quantity of operating DSSC (3 rather than 4), but it inserts more series reactance. Note that the objective function W_{B4} effectively obtains the minimum reactive power injected/absorbed by the set of DSSCs. However, owing to the nature of the function (triple product of variables, one of them binary), the computational effort is too large in practice for real-time applications, and the total reactance needed is also very high. The results when W_{B2} is adopted are detailed in Table III and shown in Fig. 4(b).

TABLE III
OPTIMAL OPERATION RESULTS OF DSSCS USING W_{B2} IN IEEE 14-BUS TEST SYSTEM

Branch *k-m*	Ampacity (kA)	w_{km} (p.u.)	w_{km} (%)	Loading level (%)	
				Without DSSC	With DSSC
1-2	0.360	0.0000	0.0	109.6	100.0
1-5	0.360	–0.0756	–33.9	53.6	62.4
2-3	0.360	0.0000	0.0	53.1	51.9
2-4	0.155	–0.0199	–11.3	95.1	100.0
2-5	0.155	0.0000	0.0	71.1	49.0
4-5	0.155	0.0421	100.0	108.3	100.0
6-13	0.077	0.0720	55.3	108.7	100.0
9-14	0.100	0.0000	0.0	56.7	56.6

The relevant transmission lines involved in the overload situation are listed along with their corresponding ampacity. The resulting compensation w_{km}, expressed in p.u. and in percentage with respect to the line reactance as well as the loading level (expressed in percentage of line ampacity) with and without DSSCs installed, are presented as well. In this scenario, a total of four DSCCs are involved in the solution, and two of them are in each range (capacitive/inductive). Activating the DSSC in line 1-5 reduces the overload of line 1-2, but can increase the loading level of line 4-5, which has alrealy been congested. To deal with this situation, an inductive DSSC is activated in the overloaded line 4-5 to reduce its own load, and a capacitive DSSC is inserted in line 2-4, taking its load to 99.98% and keeping the three lines (1-2, 2-4, and 4-5) at exactly 100% load. This is an interesting and non-intuitive solution. At the 132 kV side, a single inductive DSSC in line 6-13 solves the overload situation.

2) IEEE 118-bus Test System

With 8 line congestions, the operation results of DSSCs considering different objective functions are presented in Table IV. The obtained results confirm the problems observed with the IEEE 14-bus test system. For large systems, like in this case, both W_{B1} and W_{B2} require too much computational time to reach a solution, whereas W_{A2} provides again a suitable solution: it is much faster while the resulting total reactance is very close to the optimal value obtained with W_{B2}.

TABLE IV
OPERATION RESULTS OF DSSCS CONSIDERING DIFFERENT OBJECTIVE FUNCTIONS IN IEEE 118-BUS TEST SYSTEM WITH 8 LINE CONGESTIONS

Function	Number of DSSCs	Total reactance (p.u.)	Loss (MW)	Reactive power of DSSC (Mvar)	Computational time (s)
	0	0.000	133.76	0.00	0.2
W_{A1}	25	1.266	133.55	87.62	0.2
W_{A2}	18	0.341	135.03	34.96	4.2
W_{A3}	24	0.386	135.76	34.43	0.6
W_{A4}	13	0.490	134.87	34.02	430.0
W_{B1}	7	0.571	137.88	49.19	297.1
W_{B2}	11	0.322	134.82	32.00	86.2
W_{B3}	24	0.386	135.76	34.43	1.1
W_{B4}	12	0.388	134.71	30.50	353.3

Therefore, these tests performed with larger systems confirm that W_{A2} provides a compromise solution between computational effort and optimality, in terms of total series reactance inserted. However, in terms of the number of the devices rescheduled, which is also an important factor in real-time operation, W_{A2} still offers the margin for improvement, as many reactance values are so small that could be neglected. This means that some of the involved DSSCs could be forced to remain at the same setpoints as those before the congestion. This can be done automatically, without resorting to the binary variables involved in W_{B1} and W_{B2}, by applying the proposed methodology whose results are discussed in the next subsection.

B. Performance of Proposed Methodology

The proposed methodology combines the solution of an NLP with a clustering technique. Based on the results analyzed in the previous subsection, W_{A2} is an adequate objective function. Note that it is based on the 1-norm which leads to a smaller number of activated DSSCs, as shown in Tables II and III. In order to obtain a fair comparison, the result of the proposed methodology is compared with its MINLP counterpart, W_{B2}, where binary variables are used. The number of iterations of the sequential procedure, shown in Fig. 2, is 3 in case of applying the algorithm $k3$, while it reduces to 2 for the algorithm $k2$. This parameter has been adjusted by checking the evolution of the NLP solution.

The performance of the proposed methodology is tested in two different contexts. First, the proposed methodology is compared with the MINLP solver without imposing any constraint on the computational time required to solve the optimization problem. This comparison focuses on the computational time required to solve the problem and the optimality of the solution. Second, the proposed methodology is compared with the MINLP solver when an upper limit on the solution time is imposed to account for the real-time feature of the application. Given the fact that the computational time may depend on the location and congestion type, a statistical assessment is carried out, as described in the sequel.

1) Scenarios with Fixed Number of Congestions (Unlimited Execution Time)

Table V compares the results obtained by applying the proposed methodology ($W_{A2}+k2$ or $W_{A2}+k3$) with those provided by using MINLP solver (W_{B2}). Two types of congestions, i. e., overloading and under-voltage congestions, are tested for the sake of completeness. Overall, the results show that W_{B2} requires a larger amount of computational time to obtain a solution, owing to the need of handling binary variables. Even if a more powerful computer is used, the solution time will introduce unacceptable delays in a wide-area corrective control scheme aimed at real-time rescheduling of DSSCs for congestion relief. Besides, the proposed methodology allows finding satisfactory results in much less time. In some cases, the proposed methodology provides solutions with the same or a smaller number of operating DSSCs, and lower total absolute reactance, which is explained by the fact that the MINLP solver may stop prematurely at a local optimum.

Comparing the results between $W_{A2}+k2$ and $W_{A2}+k3$, in some cases, $W_{A2}+k3$ provides a lower total reactance, but $W_{A2}+k2$ gets the results in less time, so both of them are considered suitable for real-time application in an EMS.

2) Statistical Assessment (Capped Execution Time)

In order to further check the validity of the results discussed in the previous test cases, 50 additional scenarios are simulated for each of the three test systems with increasing number of congestions. The result comparisons of the proposed methodology and MINLP solver (W_{B2}) in all scenarios are presented in Tables VI, VII and VIII, respectively, for the IEEE 14-bus, 118-bus, and 300-bus test systems.

TABLE V
RESULT COMPARISON OF PROPOSED METHODOLOGY WITH MINLP SOLVER FOR DIFFERENT TEST SYSTEMS WITH THREE OVERLOADING OR UNDER-VOLTAGE CONGESTIONS

Congestion type	Test system	Method	Simulation time (s)	Number of DSSCs	Total reactance (p.u.)
Overloading	14-bus	$W_{A2}+k3$	3	5	0.0228
		$W_{A2}+k2$	2	6	0.0334
		W_{B2}	91	4	0.0296
	118-bus	$W_{A2}+k3$	13	5	0.0039
		$W_{A2}+k2$	7	5	0.0063
		W_{B2}	288	5	0.0058
	300-bus	$W_{A2}+k3$	46	8	0.0041
		$W_{A2}+k2$	35	6	0.0012
		W_{B2}	833	6	0.0009
Under-voltage	14-bus	$W_{A2}+k3$	3	2	0.0501
		$W_{A2}+k2$	2	5	0.0602
		W_{B2}	19	4	0.0655
	118-bus	$W_{A2}+k3$	22	6	0.3886
		$W_{A2}+k2$	10	14	0.2922
		W_{B2}	1239	10	0.1559
	300-bus	$W_{A2}+k3$	92	5	0.0041
		$W_{A2}+k2$	39	7	0.0056
		W_{B2}	434	4	0.0051

Note that, in the EMS of a typical transmission system operator (TSO) or independent system operator (ISO), monitoring and relieving the possible congestions caused by the load evolution require that the corrective control actions should be computed in very few minutes. Therefore, in all tests presented below, the solution time is limited to 180 s. If an optimal solution is not found in that time, the KNITRO® solver returns the best available solution. In this regard, two success rates SR_{fs} and SR_{os} are provided to characterize statistically the performance of the method. These indexes are calculated as follows.

1) SR_{fs} is the relative number of executions in which a feasible solution is found, even if the solution process is stopped before reaching the time or iteration limit.

2) SR_{os} is the relative number of executions in which an optimal solution is found before reaching the time or iteration limit.

As expected, in all scenarios, the number of DSSCs which are needed to operate the system securely, increases when more congestions arise in the power grid. Moreover, in most of the cases for the three methods, the DSSC reactance inserted in series also increases with the number of congestions.

Regarding the average simulation time, as concluded in the previous section, for large systems, most of the cases with more than one congestion reach the time limit when using the objective function W_{B2}. This is evidenced by a very low success rate SR_{os} when using that function. However, even if the simulation ends because the time limit is reached, the solver still finds a solution (not an optimal one, but a valid solution), which explains why SR_{fs} may have high values while SR_{os} has very low values (near 0% in some cases).

Concerning the average number of DSSCs to be operated and their total reactance in the different scenarios, the proposed methodology yields very good results at a modest computational time. The best average simulation time is achieved by using $W_{A2}+k2$, because it involves only two iterations while $W_{A2}+k3$ performs three iterations. However, the latter can find better solutions in terms of total reactance and number of DSSCs to be operated, as it can bypass some additional DSSCs during the third iteration.

TABLE VI
RESULT COMPARISON FOR IEEE 14-BUS TEST SYSTEM WITH OVERLOADING OR UNDER-VOLTAGE CONGESTIONS

Congestion type	Number of congestions	Method	Average simulation time (s)	Average number of DSSCs	Average total reactance (p.u.)	SR_{fs} (%)	SR_{os} (%)
Overloading	1	$W_{A2}+k3$	3.1	3	0.008	98	98
		$W_{A2}+k2$	1.6	2	0.015	98	98
		W_{B2}	9.5	2	0.005	98	98
	3	$W_{A2}+k3$	2.9	6	0.043	86	84
		$W_{A2}+k2$	1.8	5	0.031	86	86
		W_{B2}	49.8	4	0.018	92	90
	5	$W_{A2}+k3$	3.1	7	0.062	66	62
		$W_{A2}+k2$	2.0	8	0.087	66	62
		W_{B2}	63.7	6	0.042	82	80
Under-voltage	1	$W_{A2}+k3$	2.6	2	0.046	100	100
		$W_{A2}+k2$	1.5	2	0.046	100	100
		W_{B2}	12.8	2	0.067	100	100
	3	$W_{A2}+k3$	2.5	3	0.055	100	100
		$W_{A2}+k2$	1.6	3	0.060	100	100
		W_{B2}	22.5	3	0.060	88	88
	5	$W_{A2}+k3$	2.5	4	0.057	100	100
		$W_{A2}+k2$	1.6	4	0.058	100	100
		W_{B2}	39.0	4	0.067	76	74

TABLE VII
RESULT COMPARISON FOR IEEE 118-BUS TEST SYSTEM WITH OVERLOADING OR UNDER-VOLTAGE CONGESTIONS

Congestion type	Number of congestions	Method	Average simulation time (s)	Average number of DSSCs	Average total reactance (p.u.)	SR_{fs} (%)	SR_{os} (%)
Overloading	1	$W_{A2}+k3$	26.4	8	0.332	94	60
		$W_{A2}+k2$	13.3	6	0.031	94	70
		W_{B2}	107.1	5	0.059	94	58
	3	$W_{A2}+k3$	53.1	14	0.246	80	44
		$W_{A2}+k2$	31.4	16	0.096	80	50
		W_{B2}	179.0	18	0.197	86	20
	5	$W_{A2}+k3$	89.4	28	0.547	98	18
		$W_{A2}+k2$	64.0	23	0.545	98	26
		W_{B2}	177.4	39	0.222	80	0
Under-voltage	1	$W_{A2}+k3$	12.7	2	0.057	84	82
		$W_{A2}+k2$	6.6	3	0.052	84	84
		W_{B2}	38.5	2	0.049	96	82
	3	$W_{A2}+k3$	42.1	7	0.257	96	72
		$W_{A2}+k2$	24.5	7	0.295	96	80
		W_{B2}	136.0	8	0.225	90	40
	5	$W_{A2}+k3$	99.5	19	1.072	98	50
		$W_{A2}+k2$	36.2	21	0.891	98	62
		W_{B2}	178.6	18	0.470	84	2

TABLE VIII
RESULT COMPARISON FOR IEEE 300-BUS TEST SYSTEM WITH OVERLOADING OR UNDER-VOLTAGE CONGESTIONS

Congestion type	Number of congestions	Method	Average simulation time (s)	Average number of DSSCs	Average total reactance (p.u.)	SR_{fs} (%)	SR_{os} (%)
Overloading	1	$W_{A2}+k3$	56.4	6	0.076	100	76
		$W_{A2}+k2$	40.8	6	0.105	100	76
		W_{B2}	121.5	4	0.070	82	44
	3	$W_{A2}+k3$	179.7	29	0.490	98	28
		$W_{A2}+k2$	115.0	23	0.807	98	38
		W_{B2}	178.4	30	0.348	94	0
	5	$W_{A2}+k3$	142.3	35	1.060	100	42
		$W_{A2}+k2$	90.1	37	1.374	100	50
		W_{B2}	176.4	53	0.624	88	0
Under-voltage	1	$W_{A2}+k3$	31.5	2	0.005	92	90
		$W_{A2}+k2$	20.8	2	0.005	92	90
		W_{B2}	28.8	1	0.004	96	94
	3	$W_{A2}+k3$	96.0	13	0.162	98	62
		$W_{A2}+k2$	63.9	14	0.423	98	74
		W_{B2}	178.7	14	0.334	94	2
	5	$W_{A2}+k3$	130.4	21	0.812	100	54
		$W_{A2}+k2$	96.3	25	0.803	100	58
		W_{B2}	180.1	28	0.429	100	0

VII. CONCLUSION

This paper presents a methodology to carry out the optimal coordinated operation of DSSC in power systems using full AC power flow models. Previous approaches based on simpler DC models lack the capability to consider the mitigation of voltage violations. Moreover, as the reactive power is considered in the models, the branch loadability is more accurately computed.

The DSSCs are modular devices which can receive control settings from an EMS to enforce the compliance of security constraints (branch loading and node voltage). This leads to a non-convex complex MINLP model, for which different objective functions related with operation "cost" (some of them including binary variables) are considered and assessed. Two heuristic methods based on *k*-means clustering algorithms are proposed to reduce the computational time, so that the methodology can be used for real-time DSSC rescheduling, while at the same time keeping the solution as close as possible to the optimal one.

The optimization problem is programmed in an algebraic language and can be applied to any power system. Three power systems are thoroughly tested to evaluate the performance of the objective functions and to compare the proposed methodology. While the two heuristic methods have pros and cons, both of them provide sufficiently optimal results at a reasonable computational time compared with the MINLP solver, which is not suitable for real-time applications in realistically large-scale power systems.

Future research efforts will be devoted to designing a wide-area hierarchical control scheme, in which the local DSSC controllers follow the EMS computed settings, for the relief of steady-state congestions. While at the same time, they are able to transiently contribute to damping dynamic phenomena.

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