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FLEXIBLE ALTERNATING CURRENT TRANSMISSION SYSTEM OPTIMIZATION IN THE CONTEXT OF LARGE DISTURBANCE VOLTAGE STABILITY

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Key words: Transient voltage stability, Static var compensator, Grasshopper optimization, Genetic algorithm.

This paper presents a study on improving transient voltage stability operating conditions in power systems using flexible alternating current transmission system (FACTS) devices, namely Static var compensators (SVC), aiming at maintaining the voltage oscillations at the system's buses during the transient regime that accompanies a network disturbance between certain prescribed limits. The integration of SVC devices is done while also pursuing the optimal SVC parameters' selection and location. The case study contains a comparative analysis of the results of the optimization problem solved using two metaheuristic optimization techniques, namely Grasshopper optimization (GO) and genetic algorithm (GA).

1. INTRODUCTION

Currently, due to the continuous increase in the electricity generation from renewable energy sources, voltage stability becomes one of the most important and studied issue related to the reliable and secure operation of the electric power systems. In order to ensure a further sustainable development of solutions based on renewable energy sources and to ensure the secure operation and quality of electricity services, the impact of the new types of generators on the transient voltage stability (TVS) must be considered.

Numerous studies in the literature discuss specific issues related to the voltage stability problem in electricity grids. The modeling of the double-fed induction generator (DFIG) generators that equip the wind turbines and their ability to produce reactive power are studied in paper [1]. Paper [2] presents the adaptation of a robust control method for two FACTS devices integrated into a simple two-machine test system: a static var compensator (SVC) connected at the same bus as one of the generators and a thyristor controlled series compensator (TCSC) connected in series to one of the system lines. Paper [3] shows the specific features related to the short-term large-disturbances voltage stability (LDVS) problem, by analysing the impact of the load modelling over the LDVS. The analysis is conducted using the professional services automation (PSA) software and a simple test system with 2 generators, feeding 2 loads. Another paper that studies short-term LDVS presents a new mathematical model that take into account the influence of the asynchronous motors [4]. The proposed model treats the variation of the voltage argument by means of differential variables to obtain a hyperbolic variation of the equilibrium points of a system with several generators. The impact of the reactive power control capacity associated with FACTS devices over the LDVS is analysed in [5], where the impact of the integration of two FACTS devices, a SVC and a TCSC within two test systems (the IEEE – 6 and 9 bus test system, is considered. Paper [6] presents the influence of the system topology over the long-term voltage stability, by analysing eight possible topologies of a 6 – bus test system. The analysis is conducted with the help of several indicators based on the Jacobian matrix and using the graph theory. Paper [7] presents a practical allocation method for dynamic var sources, such as SVC or STATCOM, based on the voltage control area concept that aims to improve the LDVS performance of a network.

In this paper, the assessment of the LDVS improvement is analysed based on the reactive power compensation using one or more SVC-type compensation devices installed at the network buses. This objective is treated as an optimization problem that aims at simultaneously determining the optimal structure of the SVC compensation devices and their optimal locations. The optimization problem thus formulated is then approached using two metaheuristic optimization techniques, namely the genetic algorithm (GA) and the grasshopper optimization (GO) algorithms.

The main original contributions of this paper are: (i) addressing the problem of reactive power compensation with SVC devices for LDVS enhancement by the simultaneous optimization of the parameters / structure of the SVC devices and their location in the network; (ii) the analysis of a set of case studies using IEEE – 39 bus test system in two hypotheses regarding the absence or presence of DFIG generators, in order to highlight the influence of the integration of renewable energy sources on the LDVS and the compensation devices; (iii) implementation of two DigSilent-power factory scripts for applying the two optimization techniques, AG and GO.

The rest of the paper is organized as follows. Sections 2 and 3 present the theoretical support for assessing the degree of large disturbance voltage stability in power systems and the basic structure of a SVC device. Then, Section 4 summarizes the general formulation of the optimization problem considered in this study and the basics on the metaheuristic algorithms used to solve this problem. The case study and its results are presented in Section 5, and the last section of the paper presents the conclusions of the study.

2. LARGE DISTURBANCE VOLTAGE STABILITY ASSESSMENT

FACTS devices can be used to improve the dynamic oscillations of the bus voltages, determined by the transient regime that follows a major system event or large disturbance (short-circuit, tripping a large generator, tripping or connecting a large load, a.s.o.).

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In this paper, the improvement of LDVS is analysed from the perspective of maintaining the voltage oscillation during the transient process between an upper and a lower voltage limit, as shown in Fig. 1. As recommended in [7], the lower limit has a time variation described by eq. (1):

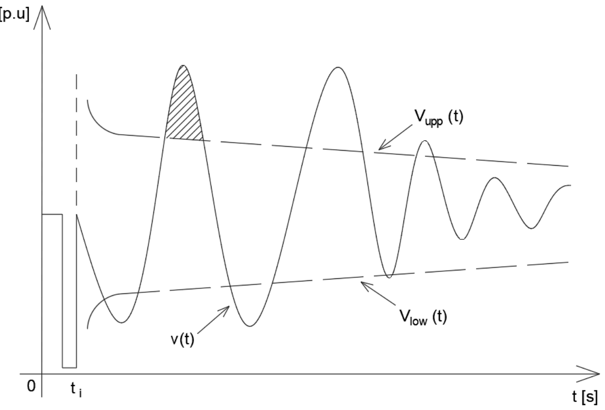

Fig. 1 – General shape of the voltage variation limits.

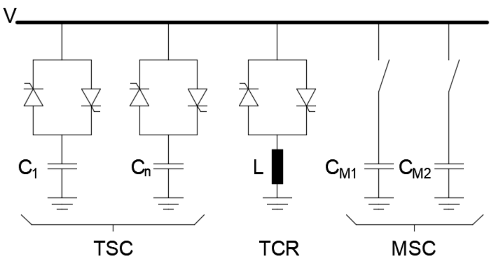

Fig. 2 – General structure of the SVC.

$$V_{low}(t) = \frac{(t/\mathrm{T}\cdot e^{t/\mathrm{T}})^{\beta}}{e^{\beta}}\cdot v_0\,, \quad (1)$$

while the upper limit is determined according to $V_{low}(t)$ as:

$$V_{upp}(t) = 2 - V_{low}(t)\,, \quad (2)$$

where: $V_{low}(t)$, $V_{upp}(t)$ – lower and upper limit voltage values at the time t; t, T – the current time and the end time of the simulation; β – damping factor of the voltage limits to the steady state voltage value v_0.

In this paper the damping factor and the steady state voltage values are considered as β=0.019 v_0= 0.9p.u. These values were chosen such that for a simulation of T=10 seconds, when the fault is removed at time t_i, the values of the limit voltages are $V_{low}(t_i)$ = 0.8 p.u., respectively $V_{upp}(t_i)$ = 1.2 p.u., and at the end of the simulation $V_{low}(T)$ = 0.9 p.u. and $V_{upp}(T)$ = 1.1 p.u. The general shape of the voltage limits variation will be similar to the one in Fig.1.

The assessment of the degree to which the voltage variation curve during the transient process falls between the imposed limits is done by following the minimization of the area delimited by the voltage variation curve $v(t)$ located outside the prescribed limits and the two limit curves $V_{low}(t)$ and $V_{upp}(t)$, as depicted in Fig. 1.

To do this, a parameter called trajectory violation integral (TVI) is defined, to to collect all the exceeding area values till the end of the simulation and is described by eq. (3).

$$\mathrm{TVI} = \int_{t_1}^{T} v'(t)\cdot dt \quad (3)$$

where the term $v'(t)$ is computed using eq. (4):

$$v'(t) = \begin{cases} v(t) - V_{upp}(t) & \text{if } v(t) > V_{upp}(t) \\ V_{low}(t) - v(t) & \text{if } v(t) < V_{low}(t) \\ 0 & \text{if } V_{low}(t) \le v(t) \le V_{upp}(t) \end{cases}. \quad (4)$$

The TVI index defined by eq. (3) is calculated for each bus and corresponds to a specific operating condition of the network. In this study, the simultaneous optimization of SVC parameters / structure and their location is done considering several possible operating conditions, corresponding to contingencies such as short circuits on electric lines, generator tripping, large consumer tripping or connection etc. Under these conditions, a new index, called contingency severity index (CSI) is defined, which aggregates the TVI values for all buses i in the network and a certain contingency k, as defined in eq. (5):

$$\mathrm{CSI}^k = \sum_{i=1}^{N}\mathrm{TVI}_{i,k}\,, \quad (5)$$

where N - total number of buses and $\mathrm{TVI}_{i,k}$ is the TVI value for contingency k at bus i. Finally, a single quality index can be defined for the entire network and for all the contingencies under consideration, called total contingency severity index (TCSI), according to eq. (6):

$$\mathrm{TCSI} = \sum_{k=1}^{NN}\mathrm{CSI}^k\,. \quad (6)$$

3. THE SVC STRUCTURE

The general structure of a SVC consists of three main components, as shown in Fig. 2, namely: a set of thyristor-switched capacitors (TSC), a thyristor controlled reactor (TCR) and a set of mechanically-switched capacitors (MSC) [12].

In this paper it was considered that the SVC device uses only the first two components, namely TSC and TCR. According to Fig. 2 the specific parameters of these two components are the following:

- for TSC: $\mathrm{TSC}_{\mathrm{MaxNo}}$ – the maximum number of capacitors and Q_{perC} – nominal reactive power per capacitor.
- for TCR: $\mathrm{TCR}_{\mathrm{MaxLim}}$ – the nominal reactive power of the reactance and $\mathrm{TCR}_{\mathrm{Q}}$ – the maximum reactive power of the reactance.

The TCR parameters will always be chosen in such a way that $\mathrm{TCR}_{\mathrm{MaxLim}}$ will never have a higher value than $\mathrm{TCR}_{\mathrm{Q}}$. Also, by convention, the nominal reactive power of the capacitor is considered negative.

By properly choosing the values of these parameters, a certain degree of performance of the respective SVC device will result, characterized by certain limits of variation of the reactive power injected or absorbed in and from the bus in which that device is to be installed, so as to ensure a certain level of the voltage in the respective bus.

4. METAHEURISTIC ALGORITHMS

As already mentioned, two metaheuristic techniques, namely GA and GO, were used to solve the optimization problem defined to improve the LDVS. This section presents the formulation of the optimization problem to improve LDVS and the fundamental elements regarding the two metaheuristic optimization algorithms.

4.1. FORMULATION OF THE OPTIMIZATION PROBLEM

According to the theoretical support presented in Section 2, the LDVS improvement implies the maintenance of the curve describing the voltage wave oscillations during the transient regime that accompanies the fault between the lower and upper limit curves, as shown in Fig. 2.

Basically, this is achieved by installing a number of SVC devices in the network (in this case 3 SVCs). By compensating the reactive power, these devices allow maintaining the voltage profiles in the network between certain limits, both in normal and transient operating conditions. In this study, the optimization problem was formulated taking into account only the transient regime, aiming to determine those locations and values of the SVC parameters that minimize the objective function in (7).

In this context, using the set of indices defined in section 2 ($\mathrm{TVI}_{i,k}$, CSI^k and TCSI), the objective function of the optimization problem is defined, according to eq. (7).

$$F_{obj} = \min(\mathrm{TCSI}) = \min\left(\sum_{k=1}^{NC} \mathrm{CSI}^k\right) = \min\left(\sum_{k=1}^{NC} \sum_{I=1}^{N} \mathrm{TVI}_{i,k}\right) \tag{7}$$

4.2. THE GENETIC ALGORITHM

The genetic algorithm (GA) is a step forward of Evolutionary Strategies in the general framework of Evolutionary Computation. GAs have been designed and developed by Holland [9], Goldberg [11] and De Jong [10].

GAs are search strategies that are based on specific mechanisms of genetics and natural selection, using three basic operators: selection, crossover and mutation. For each generation, selection is used to choose parent individuals, based on their fitness function. After selecting a pair of parent chromosomes, they enter the crossover stage to generate two offsprings.

Crossover is useful to create new individuals or solutions that inherit good characteristics from both parents. Newly created individuals will be altered by small-scale changes in the genes, applying mutation operator. Mutations ensure the introduction of "novelty" in the genetic material. After completing the offspring population, this will replace the parents from the previous generation and the selection-crossover-mutation process will be resumed for a next generation.

To avoid losing the best solution due to the stochastic nature of the search process, a special replacement procedure called "elitism" was proposed to make a copy of the best individual from the current population and transfer it unchanged in the next generation.

4.3. THE GRASSHOPER ALGORITHM

The grasshopper optimization algorithm (GOA) is inspired by how grasshoppers are organized, insects known to be very dangerous pests for agriculture [8]. Moving into the search space to identify the solution to an optimization problem is done in this case simulating the movement of the grasshoppers under the attraction or repulsion forces, in the presence of a comfort zone, where the grasshoppers no longer interact. The action of these forces is modeled by a function describing the degree of insects' socialization:

$$s(r) = f \cdot e^{-r/l} - e^{-r} \tag{8}$$

where r is the distance between two grasshoppers, and f and l are two control parameters.

Grasshoppers' position is updated using two terms. The first term establishes the new position X_i according to the positions of all other grasshoppers / solutions X_j, using the social function $s(r)$, where distance r is calculated as

N1	N2	N3	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4

Fig. 3 – Structure of a chromosome to represent a possible solution of the LDVS optimization problem.

$$r = \left| X_j - X_i \right|. \tag{9}$$

The second term is the so-called "target", represented by the best solution identified so far. These terms are correlated by an adaptive parameter c, which gradually decreases its value from the first to the last iteration, between a maximum and a minimum value (c_{min}, c_{max}). Parameter c contributes on the one hand to balancing the exploration and exploitation processes around the target (the optimal solution) and on the other hand, it allows the control of the attraction zone, comfort zone and repulsion zone to describe the interaction between grasshoppers / solutions. As indicated in [8], the values selected for parameters f, l, c_{min} and c_{max} influence the results of the algorithm and, in particular, its convergence properties.

4.4. SOLUTION REPRESENTATION

For both metaheuristic algorithms a possible solution of the optimization problem is represented according to the chromosome shown in Fig. 3. Thus, the chromosome consists of four sections. The first section contains a number of genes equal to the number of available SVCs, in the present case 3 (noted N1, N2, N3). Each gene contains the number of the bus where that SVC is located. Obviously, the values entered between the three genes must be different. The following three sections that are identical in structure contain the parameter values (noted P1, P2, P3, P4) for each of the three SVCs. These parameters correspond to the parameters of the TSC and TCR devices: $\mathrm{TSC}_{\mathrm{MaxNo}}$, Q_{perC}, $\mathrm{TCR}_{\mathrm{Q}}$ and $\mathrm{TCR}_{\mathrm{MaxLim}}$. With respect to the structure of the chromosome from Fig. 3, we mention that within the AG a three-point crossover operator is used.

5. CASE STUDIES

In this paper the problem described in the previous sections was solved for the New England 39– bus test system [13], for two particularly scenarios, namely: S1 – the test system without any wind penetration and S2 – the modified test system by replacing the synchronous generator (SG) G08 from bus 37 with a 500 MW wind farm (WF) at bus 7.

The New England 39 – bus test system is a power grid with 39 buses and 4 voltage levels. The main voltage level of the grid is 345 kV, whereas the additional three other voltage levels are applied for power generation or consumption.

The system comprises 9 power generators and the generator G2, which is indicated as reference machine.

Most of the generators are mostly connected to the grid through a medium voltage bus and a step-up transformer. A special case is the generator G1, which is directly connected to a high voltage bus, because it represents a generic source.

The WF consists of 125 wind generators with 4 MW rated power considered to compensate the entire power produced by the SG from bus 37. The WF is connected at bus 7 through two high voltage lines of 10 km each. WF location was considered randomly, just to test the ability of the proposed method to improve the voltage stability conditions.

Table 1

The values of the contingency severity index CSI^k

Contingency location	Scenario S1							
	C1		C2		C3		C4	
	BUS	**CSI^k [p.u.]**	**BUS**	**CSI^k [p.u.]**	**BUS**	**CSI^k [p.u.]**	**BUS**	**CSI^k [p.u.]**
Line 16-19	19	1.57	19	1.59	19	1.26	19	1.29
Line 26-29	29, 38	0.08	-	-	-	-	-	-
Line 28-29	26, 28, 29, 38	42.08	29, 38	1.57	-	-	-	-
TCSI [p.u.]	**43.73**		**3.167**		**1.26**		**1.29**	
	Scenario S2							
Line 16-19	19	1.58	19	1.70	19	1.43	19	1.31
Line 26-29	29, 38	0.05	-	-	-	-	-	-
Line 28-29	26, 28, 29, 38	55.18	29, 38	9.52	-	-	-	-
TCSI [p.u.]	**56.81**		**11.22**		**1.43**		**1.31**	

Table 2

The optimal solutions given by GA and GO in situation S1

Optimized value	GA	GO
SVC 1 Location	**Bus 1**	**Bus 11**
Q_{perC}	-1 Mvar	-6 Mvar
TSC_{MaxNo}	2	14
TCR_Q	7 Mvar	13 Mvar
TCR_{MaxLim}	5 Mvar	3 Mvar
SVC 2 Location	**Bus 15**	**Bus 15**
Q_{perC}	-7 Mvar	-7 Mvar r
TSC_{MaxNo}	21	23
TCR_Q	5 Mvar	3 Mvar
TCR_{MaxLim}	3 Mvar	2 Mvar
SVC 3 Location	**Bus 29**	**Bus 29**
Q_{perC}	-8 Mvar	-6 Mvar
TSC_{MaxNo}	3	21
TCR_Q	10 Mvar	16 Mvar
TCR_{MaxLim}	4 Mvar	7 Mvar
Objectiv function	1.26 p.u.	1.29 p.u.
Computation time	493 min.	476 min.

Table 3

The optimal solutions given by GA and GO in situation S2

Optimized value	GA	GO
SVC 1 Location	**Bus 1**	**Bus 7**
Q_{perC}	-5 Mvar	-6 Mvar
TSC_{MaxNo}	15	18
TCR_Q	6 Mvar	13 Mvar
TCR_{MaxLim}	4 Mvar	3 Mvar
SVC 2 Location	**Bus 8**	**Bus 15**
Q_{perC}	-6 Mvar	-7 Mvar
TSC_{MaxNo}	15	4
TCR_Q	12 Mvar	4 Mvar
TCR_{MaxLim}	3 Mvar	2 Mvar
SVC 3 Location	**Bus 29**	**Bus 29**
Q_{perC}	-1 Mvar	-6 Mvar
TSC_{MaxNo}	4	15
TCR_Q	15 Mvar	14 Mvar
TCR_{MaxLim}	8 Mvar	7 Mvar
Objectiv function	1.43 p.u.	1.31 p.u.
Computation time	744 min.	728 min.

For the two scenarios, other four cases were considered with respect to the SVC devices: C1 – the base case without any SVC; C2 – the test system plus three SVCs, with randomly selected parameters and locations within the allowable limits, to illustrate a non-optimized case; C3 – the test system with optimized locations and parameters for the three SVC provided by the GA optimization model; C4 – the test system with optimized locations and parameters for the three SVC provided by the GO optimization model. For case C2 the 3 SVC were located at buses 6, 16 and 25, and the rated parameters are: Q_{perC}=-7 Mvar; TSC_{MaxNo}=15; TCR_Q=10 Mvar and TCR_{MaxLim}=2 Mvar.

For each case, three contingencies were considered, corresponding to tripping of lines 16-19, 26-29 and 28-29 (number of contingencies, NC = 3).

The main parameters of the models used in this study are the following:

- number of generations/ iterations: 20.
- number of chromosomes /agents: 30.
- TCR_Q range of values: [1:20] [Mvar].
- TCR_{MaxLim} range of values: [1:10] [Mvar].
- TSC_{MaxNo} range of values: [1:25].
- Q_{perC} range of values: [-1:-10] [MVAr].
- GA parameters: crossover probability: 0.7; mutation probability: 0.2.
- GO parameters: f = 0.65; l = 1.5.

The analysis was performed using the software application DigSilent Power Factory [12]. Using the capabilities of the DPL (DigSilent Programming Language) module, two scripts were designed to implement the two optimization techniques, AG and GO.

For the calculation of the TVI and CSI indices, the voltage variation curves $v(t)$ were recorded for T = 10 s using a sampling interval Δt = 0.01 s, small enough for an appropriate resolution.

The results obtained by applying the proposed method for the two scenarios S1 and S2 and the four particular cases C1, C2, C3 and C4 are presented in Tables 1 - 3 and Figures 4–7.

Table 1 shows the values of the CSI^k and TCSI indices provided by the proposed calculation model for the two scenarios and the four particular cases. In this table, for each contingency and each case, two values are shown: index CSI^k and the bus or buses where the voltage limits are violated, determining a non-zero value of index CSI^k. When the voltage limits are exceeded in several buses (for example, for scenario S1, case C1 and contingency "Line 28-29" the voltage limits are exceeded in 4 buses, namely 26, 28, 29, 38), the value indicated for index CSI^k represents the cumulative value of the indices in those buses. When voltage limits are not exceeded, no values are indicated either for index CSI^k or for the buses.

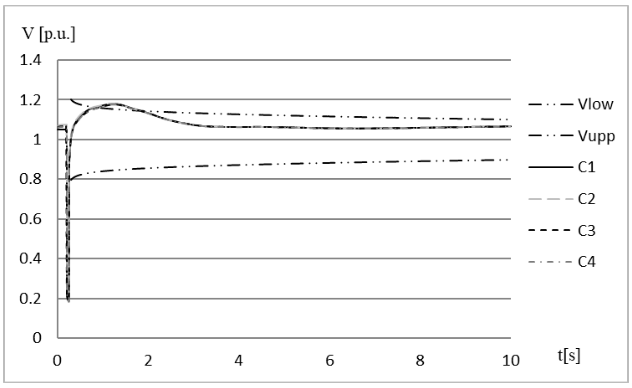

Fig. 4 – Bus 19 voltage variation in situation S1.

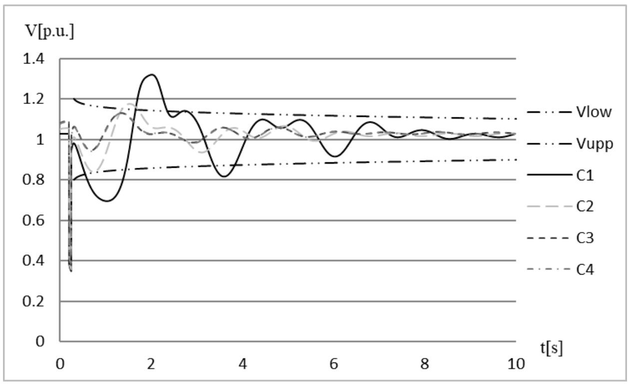

Fig. 5 – Bus 38 voltage variation in situation S1.

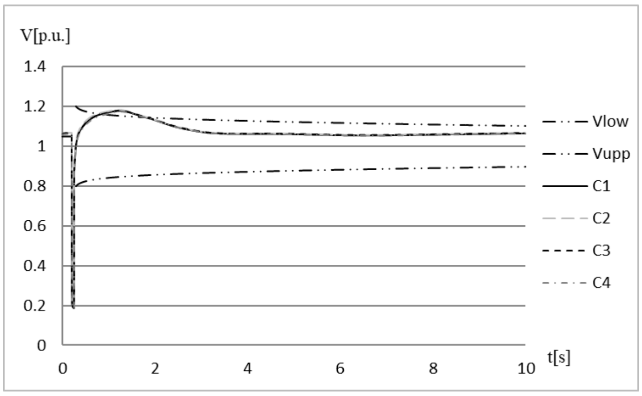

Fig. 6 – Bus 19 voltage variation in situation S2.

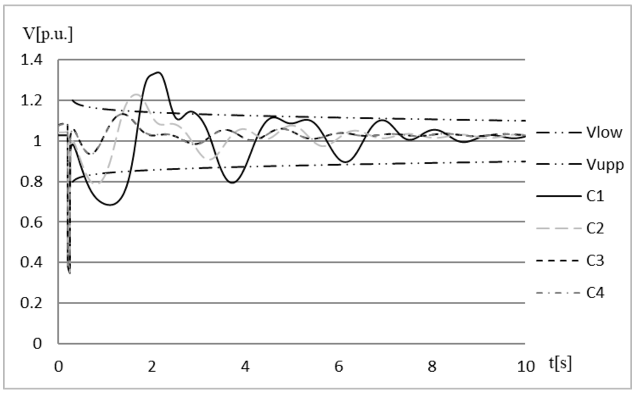

Fig. 7 – Bus 38 voltage variation in situation S2.

The analysis of the data in Table 1 shows that in case C1 (the original test system, without compensation) the voltage limits are exceeded in a greater number of buses than for the cases that use SVC-compensation. Thus, in both scenarios S1 and S2 and for all the contingencies considered, the voltage limits are exceeded in 7 buses (case C1), 3 buses (case C2) and a single bus (cases C3 and C4). This fact highlights the positive effect that the SVC installation has on LDVS improvement. These values also illustrate the positive effect of the optimal sizing and placement of SVC devices: the number of buses where voltage limits are exceeded decreases from 3, in case C2 (random compensation), to 1, in cases C3 and C4 (optimized compensation). As expected, for both scenarios the performance of the non-optimized SVCs is lower than in cases of optimized locations and parameters.

Hence, from the point of view of the optimization process, data in Table 1 show that the best values of parameters TVI and CSI^k are obtained in cases C3 and C4. On the other hand, the data from the same tables reflect the effect of WF integration on LDVS: one can observe that in the case of scenario S2 the voltage wave oscillations are amplified, which corresponds to higher values of the *TCSI* and CSI^k indices.

Tables 2 and 3 indicate the optimal compensation solutions (optimal locations and optimal parameters) for cases C3 and C4, in the two scenarios. The data in Tables 2 and 3 show that, due to the stochastic nature of the two types of metaheuristic algorithms, the optimal solutions provided by each of them, although characterized by close values of the objective functions (1.26 p.u. for GA-case C3 and 1.29 p.u. for GO-case C4, for scenario S1, respectively 1.43 p.u. for GA-case C3 and 1.31 p.u. for GO-case C4 for scenario S2), they can differ significantly in terms of SVC parameters and locations.

Also, the last two rows in Tables 2 and 3 contain the values of the objective function and the computation time recorded for running the DPL scripts for the two optimization algorithms, GA and GO.

The high computation times indicated in Tables 2 and 3, of the order of hundreds of minutes, are determined by the large volume of calculations involved in the simulation process that provides voltage variation curves as in Fig. 1, for calculating the $TVI_{i,k}$, CSI^k and TCSI indices. Thus, at the level of the DPL script, computing times are allocated for two types of evaluations: (i) stationary power flows for evaluating the initial conditions of the dynamic regime associated with a contingency and (ii) simulation of the dynamic voltage variation at each bus in the network for a number total $T / \Delta t = 1000$ samples. However, the high values of the computation times are not a major drawback, because the proposed model is not intended to online application, but to system analysis and development studies related to system security and electricity supply continuity.

To illustrate how the voltage wave oscillations at network buses fall within the prescribed limits or not, the following provides information on the voltage variation at two buses as a result of the associated contingencies:

- bus19, and short-circuit on line 16-19.
- bus 38, and short-circuit on line 28-29.

Voltage profiles at selected buses for the two scenarios regarding the presence or absence of the WF are shown in Fig. 4-7. In these figures the voltage limit curves are drawn with a long dashed double dotted black line. Also, the curves in these figures use the following convention:

- Case C1 is represented by a continuous black line.

- Case C2 is represented by a long dashed grey line.
- Case C3 is represented by a dashed black line.
- Case C4 is represented by a dashed dotted dark grey line.

It is mentioned that for cases C3 and C4, when the SVC devices are optimally located using one of the two metaheuristic algorithms, the two curves are very close, and in Fig. 4 – 7 they practically overlap.

Figs. 5 and 7 show that the highest voltage oscillations and exceedances of the prescribed limits were recorded at bus 38 for cases C1 and C2. At the same time, for the optimized cases C3 and C4, the voltage wave oscillations at bus 38 are totally within the prescribed limits.

On the other hand, for bus 19 the voltage oscillations shown in Fig. 4 and 6 are quite different: in all cases the oscillations are much attenuated compared to those of bus 38 and are similar for all four cases C1 – C4. Their magnitude is small, registering a slight exceedance of the upper limit at the first oscillation.

According to Fig. 7, the voltage variations increase significantly at bus 38, especially in cases C1 (without compensation) and C2 (random compensation) in scenario S2 (WF integration), and are much attenuated in cases C3 and C4 (optimized compensation), for both scenarios S1 and S2 (without and with WF integration).

The values of the TCSI index in Tables 1 – 3 indicate significant improvements in the system's performance as a result of SVC compensation. Thus, in the case of scenario S2, the TCSI index decreases from 56.81 p.u. in the base-case (without compensation) to 11.22 p.u. in the case of random compensation (C2). The reduction is even higher, up to 1.43 p.u. or 1.31 p.u., in the case of optimal compensation using one of the two metaheuristic algorithms (cases C3 and C4).

A comparison between the results provided by the two metaheuristic algorithms shows that the GO algorithm leads in all cases to shorter computation times, while the values of the objective function are of the same order of magnitude and similar for both algorithms, GA and GO. On the other hand, the data in Tables 2 and 3 show that the two metaheuristic algorithms lead to much different structures of the optimal solutions. This fact illustrates the wide diversity of the possible network compensation solutions. Overall, it can be seen that the GO algorithm performs better compared to the GA algorithm.

6. CONCLUSIONS

The analysis of the dynamic behavior of voltage profiles at the buses of electrical power systems showed that renewable sources integration could significantly impact over the LDVS when measures are not taken to compensate the reactive power using SVC-type FACTS devices. The use of such compensation devices, simultaneously with their optimal location and sizing, contributes to the significant improvement of the dynamics of voltage profiles at network buses and of the general voltage stability level in the system.

The case studies presented in this paper were conducted for two scenarios regarding the absence or presence of renewable energy sources, as well as in different hypotheses regarding the use of SVC-type compensation devices.

In all cases, the optimization problem formulated takes into account the dynamics of the voltage variations at the system's buses as a result of an event / contingency produced in the network and aims to maintain as much as possible the voltage profile between certain prescribed limits. The optimization problem was solved using two metaheuristic algorithms, namely the Genetic Algorithm and the Grasshopper Optimization Algorithm.

The results confirm the ability of the proposed model and optimization methods to maintain the voltage variation profile within the prescribed limits using the reactive power compensation with SVC devices and highlight similar or superior performances of the GO algorithm.

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