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MVMO-based tuning of Active Power Gradient Control of VSC-HVDC links for Frequency Support

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***Abstract*—The active power gradient (APG) control of MMC-HVDC links can contribute to frequency support in AC networks affected by severe active power imbalances. This functionality is particularly convenient if the coupled AC systems (through MMC-HVDC) have similar levels of available inertia. This paper tackles the problem of determining the optimal APG parameters that entail bounding frequency excursions within acceptable limits while helping to quickly damp out electromechanical oscillations. The tuning task is tackled as a single objective computationally expensive optimization problem. Since the optimization search procedure involves repetitive time-domain (RMS) simulations, the major challenge resides in solving the problem within reduced amount of fitness evaluations. In view of this, an emerging metaheuristic algorithm, namely, the mean-variance mapping optimization (MVMO) is selected. Numerical results prove the effectiveness of MVMO in finding the optimal solution within a few fitness evaluations.**

Keywords—Active power gradient, frequency control, MVMO, VSC-HVDC.

I. INTRODUCTION

Traditionally, the governor systems of conventional power plants with synchronous generators have been responsible for ensuring that the frequency of an electrical power system remains within acceptable technical limits. Nevertheless, governors usually entail time delays (e.g. between 2s and 6s) [1], which affect the speed of delivery of active power reserves of synchronous generators whenever a power imbalance occurs in the system.

By contrast, modern voltage source converter based high voltage direct current systems (VSC-HVDC) offer the possibility of delivering active power within a very reduced time period, e.g. 1000 MW/s active power ramp rate or active power gradient (APG) [2]. This property of VSC is motivating research efforts aiming at designing different methods for frequency control by adjusting the APG of VSC interfaced generation. Most of the recent work has been devoted to frequency control in solar photovoltaic systems [3]-[4]. Other research efforts are focused on delta active power control in solar photovoltaic systems [5], or the DREG function in VSC-HVDC links [6].

It is worth pointing out that the design of the APG is being considered among several grid code requirements for integration of VSC interfaced devices. For instance, the APG is considered in UK as part of the enhanced frequency response (EFR) requirements [7]. Remarkably, as shown in the preliminary research outcomes provided in [8], a fast regulation of the active power transfer through a VSC-HVDC can be beneficial for frequency support towards the synchronous areas connected to the AC side of the VSC converters, especially when the areas have a significant difference in terms of area inertia and capabilities for primary frequency control. In [8], it is shown that the settings of the APG may play an important role for mitigation frequency excursions when the synchronous areas have similar level of inertia and the VSC-HVDC link entails a considerable amount of active power transfer between the areas. It is worth mentioning that several research works gave focused on the use of Linear Quadratic Regulator (LQR) based method. In LQR based method, the control design for the developed model is critical, especially if the model under study is complex with high number of state variables that should be controlled [11]. Furthermore, the significance of the input noise can also limit the performance of the controller, whereas using a heuristic based method for better tuning and design of LQR controller may be an alternative solution as suggested in [12]-[13].

Based on findings from [8], this paper concerns with the development of a method for optimal tuning of the APG of VSC-HVDC links. The problem of tuning is defined as an optimization problem that minimizes the frequency deviation over time with respect to a reference frequency value. This entails a significant computational burden, because root-mean-square (RMS) simulations should be performed to obtain the time series of nodal frequency as measures in the synchronous areas connected to the VSC-HVDC link. To tackle this issue, the paper applies a powerful heuristic optimization algorithm, named as mean-variance mapping optimization (MVMO). MVMO has been successfully applied in recent research works to tackle hard-to-solve (e.g. multimodal, nonconvex) computational expensive optimization problems [9]-[10].

This paper also introduces a modification to MVMO, which consists of performing the generation of random numbers used in the initialization and the rules evolutionary mechanism of MVMO by using Latin-hypercube sampling (LHS) [4]. LHS prevents obtaining random samples that are concentrated around a specific region of the probabilistic distribution function (e.g. uniform) that characterizes the variability of a random variable. Hence, the purpose of introducing LHS in MVMO is to attempt to sample more efficiently the whole search space of the optimization variables. As a case study, the well-known two-area four-machine system is modified to include a VSC-HVDC link.

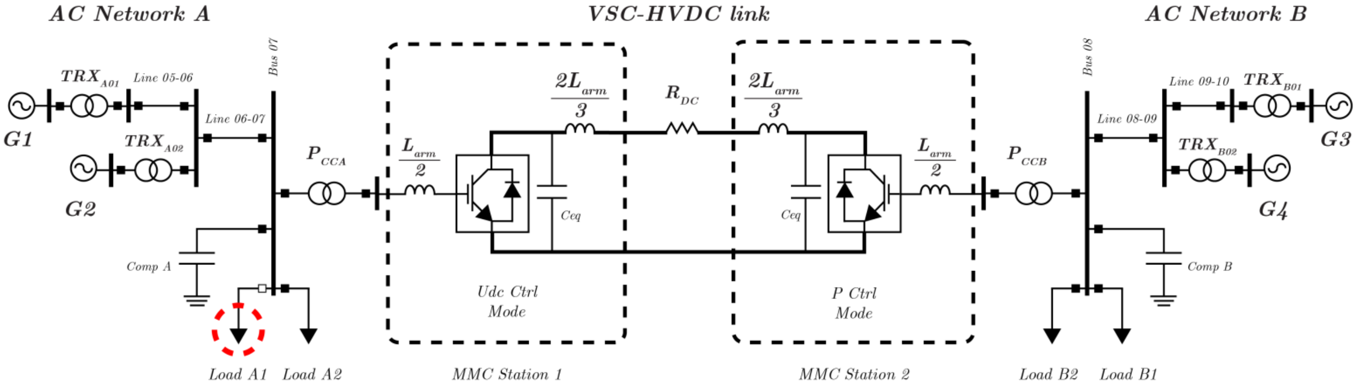

Figure 1. Modified two-area four-machine system from [1]. The original link (transmission lines) between the two AC networks has been replaced by the VSC-HVDC system from [8].

This system is used to demonstrate the effectiveness of the MVMO-based method for optimal tuning of APG and the amount of power that should be transferred between the 2 synchronous areas through the VSC-HVDC. The reminder of the paper is structured as follows: Section 2 presents the optimization problem formulation. Section 3 provides a short overview of MVMO. Numerical results are shown in Section 4. Finally, concluding remarks are summarized in Section 5.

II. PROBLEM FORMULATION

As indicated in [14], the rate of change of frequency associated to an active power imbalance of around 20% in an interconnected electrical power system may lie in the range of 500 mHz/s – 1 Hz/s. This imbalance is usually mitigated by the governor systems attached to the synchronous generators in operation in the system. Nevertheless, as shown in [8], it is also possible to provide frequency support by regulating the active power injection of a VSC-HVDC link. The study presented in this paper bases on the modified version of the two-area four-machine system used in [8].

The modification done essentially consists in the addition of a VSC-HVDC link. The layout of the modified system is shown in Figure 1. The considered imbalance is attributed to an approximately 20% sudden decrease of active power demand in the AC network A (highlighted with a red circle in Figure 1). Besides, it is considered that both AC networks have similar level of inertia. An overview of the system generation, demand, and inertia is provided in Table I.

It is worth pointing out that [8] focused exclusively on the implementation of a strategy for frequency support and its impact on the dynamic frequency performance, within a time frame of 2 min, of the AC network A (cf. Figure 1). The implemented strategy allows to change the total active power reference (P_{pu_ref}, cf. Figure 2) of the active current control channel of the corresponding VSC station. Figure 2 illustrates the strategy implemented in [9], which is now extended to consider its tuning based on an optimization task, solved via MVMO (cf. block highlighted with yellow in Figure 2).

Table I – Generator Inertias and Load Flow Description

Generation and Demand	System Element	Load Flow Conditions (MW)	Generators Inertia (s)
Generation on Area A	G1 G2	700 700	6,5 6,5
Demand on Area A	Load A1 Load A2 MMC station 1	250 717 400.5	N/A N/A N/A
Generation on Area B	G3 G4 MMC station 2	719 700 381.6	6,175 6,175 N/A
Demand on Area B	Load B1 Load B2	250 717	N/A N/A

The MVMO optimization algorithm determines the optimal value of active power deviation (i.e. the optimum ΔP) as well as the optimal value of the slope associated to the active power rate limiter (i.e. the optimum APG).
To define the problem of simultaneous optimization of the APG and the power transfer through the VSC-HVDC, it is considered in this study that the frequency support is performed by the simultaneous participation of the synchronous generators in both AC networks, supported by the strategy for frequency control attached to the VSC-HVDC link. In this way, the VSC-HVDC link constitutes a mean to regulate the degree of participation of the synchronous generators (associated inertia and governors) in the mitigation of a frequency excursion due to a sudden load step in the AC network A.

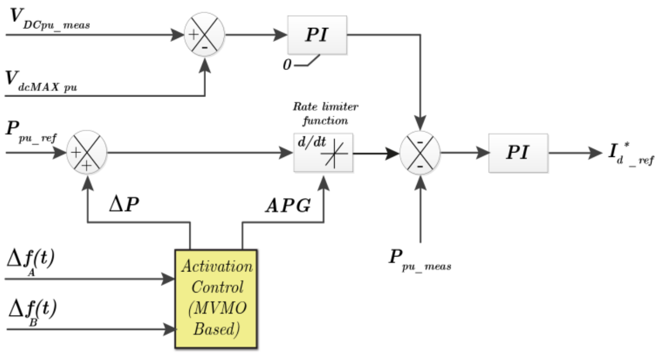

Figure 2. Modified Active Power control scheme [15] of the MMC-HVDC station 2, including the MVMO algorithm.

The degree of participation of the synchronous generators is reflected in the instantaneous electrical frequency change (i.e. the $\Delta f_i(t)$ associated to the change of the kinetic energy in each AC network) that is perceived by the AC buses of the VSC stations conforming the HVDC link (i.e. bus 07 y bus 08 in Figure 1). This frequency change is also affected by the APG and the active power deviation (ΔP) transferred by the HVDC link as shown in Figure 2. Therefore, the optimization problem is defined as follows:

Minimize

$$\mathrm{OF} = \int_0^{\tau} \left[\mathrm{w}_1 \left(y_i(\mathbf{x}) - y_{1_{\mathrm{ref}}} \right)^2 + \ldots + \mathrm{w}_n \left(y_n(\mathbf{x}) - y_{n_{\mathrm{ref}}} \right)^2 \right] dt \qquad (1)$$

subject to

$$\mathbf{x}_{\min} \le \mathbf{x} \le \mathbf{x}_{\max} \qquad (2)$$

where w_i denotes a weight factor (set to 1 in this paper), y_i is the measured frequency at the AC side (point of common coupling bus) of the corresponding VSC station, and y_{ref} is the nominal value of the frequency in the AC network connected to the VSC. The optimization vector $\mathbf{x}$ is defined by (3) (cf. APG and ΔP are defined in Figure 2).

$$\mathbf{x} = \left[\mathrm{APG} \quad \Delta\mathrm{P} \right] \qquad (3)$$

where:

$$1 \frac{\mathrm{MW}}{\mathrm{min}} \le \mathrm{APG} \le 60 \frac{\mathrm{GW}}{\mathrm{min}} \qquad (4)$$

$$0 \le \Delta\mathrm{P} \le P_{VSC\_Rated} \qquad (5)$$

The optimization problem defined in (1)-(3) attempts to emulate what would happen if the two AC networks were interconnected by AC tie-lines. The limits defined in (4) were taken from [2]. Next section will illustrate the impact caused by the frequency performance obtained when the VSC-HVDC has frequency control vs. the case when the two areas are connected by an AC transmission line (i.e. the original system shown in [1]).

III. MVMO DESCRIPTION

The overall procedure of MVMO is illustrated in Fig. 3. In the initialization stage, random values are drawn for the APG, ΔP, and the parameters used by MVMO for the evolution of the solution throughout the optimization search procedure. Unlike [9], MVMO is modified in this paper to use LHS instead of random sampling. In this way, it is expected that MVMO covers the whole search space more uniformly and this can lead to a faster convergence. The parameters of MVMO presented in [9] were used in this paper.

Note that MVMO performs the evolution of the solution within a normalized search space, i.e. the APG and the ΔP are normalized from their [min, max] bounds (cf. (4) and (5)) to the range [0,1]. However, de-normalization of APG and ΔP is performed when the values generated by MVMO for APG and ΔP are used for fitness evaluation. The fact that MVMO works with a normalized search space entails that the bound constraints defined by (2) are always satisfied. Unlike other evolutionary algorithms, this also avoids the need of using additional strategies for correcting generated solutions that can have new generated values of the optimization variables outside the allowed bounds. Fitness evaluation mean the actual calculation of (1). To this aim, a script is created in Python. The script runs the MVMO code from Matlab, collects the values of APG and ΔP proposed by MVMO, and then substitutes these values in the model of the VSC-HVDC built in DIgSILENT PowerFactory. The Python script also executes time domain simulations in PowerFactory to obtain the time series of the frequency response as measured at the AC side of the VSC station. Equation (1) is then computed by using the time series of the frequency response.

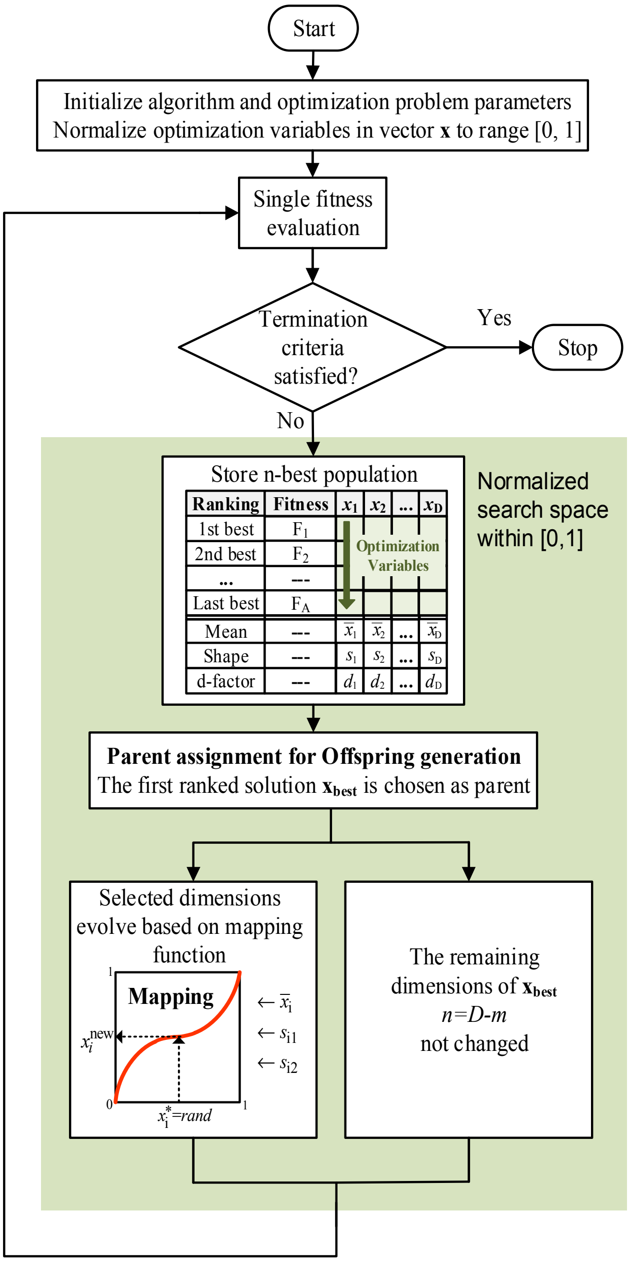

Figure 3. Algorithmic procedure of MVMO. The fitness evaluation counter is denoted by i. Source [9]

MVMO generates new solutions throughout the optimization process based on the best solution found so far. For this purpose, the algorithm has a solution archive, in which the values of the n-best evolved solutions in the last n-function evaluations are stored. This information is used to compute mean value, variance, and shape factors of each optimization variable. These statistical measures are inputs of the so-called mapping function, which is used to generate a new value of the selected optimization variable from the vector corresponding to the best solution found so far. In this paper, the termination criterion is defined as the fulfilment of a pre-defined number of function evaluations. The reader is referred to [9] for detailed formulation of the evolutionary operations of MVMO.

IV. NUMERICAL RESULTS

A. System Description

The tie-lines used in the original version of the benchmark system, as presented in [1], have been replaced by the generic model of VSC-HVDC system presented in [8]. This replacement was done by considering the power flow profile within each synchronous area as defined in the original version of the benchmark [1] system. That is, the active and reactive power set-points of the VSC-HVDC system have been defined such that both synchronous areas have the same power flow profile conditions like in the original version of the benchmark [1] system. The control systems (i.e. excitation system, and governor system) of each generator shown in Figure 1 are represented by using a steam governor and the IEEE AC4A excitation system. These systems are described in detail in [1].

The modelling of the VSC-HVDC link presented in Figure 1 was based on the average models (AVM) illustrated in [15] and [16]. Specifically, the VSC-HVDC model type 6 from [15] and the model type 4 from [16] were utilized. These models were considered since they are intended to perform quasi-stationary or root mean square (RMS) type of simulation experiments, which are necessary tools for the study of the frequency stability in power system.

The control systems associated to the VSC-HVDC link from Figure 1 are described in detail in [15]. Particularly, the active power control system from [15] was adapted to include the MVMO optimization algorithm as shown in Figure 2.

B. Results

B.1. Original benchmark system response.

The evaluation of the frequency response of the system was done by considering the occurrence of an imbalance in the AC network A, which is created by disconnecting the Load A1 (cf. Figure 1) at t = 1 s. In the original version of the benchmark system shown in [1], the two AC networks are connected through two parallel AC tie-lines. The Figures 4a and 4b show the dynamic response of the generators' rotor speed and the mechanical power of all turbines, respectively. Figure 4a shows that the disconnection of Load A1 entails that the generators reach a steady-state value of approximately 1.005 pu. Figure 4a also shows that the peak value of the generators' rotor speed in approximately 1.012 pu. Note also in Figure 4a that inter-area oscillations are presented by the occurrence of the imbalance in the network Area A. The inter-area oscillations effects are also observable in the mechanical powers shown in Figure 4b.

B.2 System response (with the AC tie-lines replaced by the VSC-HVDC link) with non-optimized APG and ΔP values

As it was described in [1], the activation of the ΔP and the APG is based on the rate-of-change-of-frequency (RoCoF). The RoCoF is computed within 500ms from the time of occurrence of the imbalance. The following criterion is used to enable frequency support by the corresponding VSC station: if the computed value (by sensing the frequency at the AC side of the VSC, e.g. Bus 07 in Figure 1) of the RoCoF is higher (for more than 500ms) than a predefined threshold (e.g. 400mHz/s was used in this case study), the active power control shown in Figure 2, will modify the amount of active power (ΔP) and the APG of the VSC

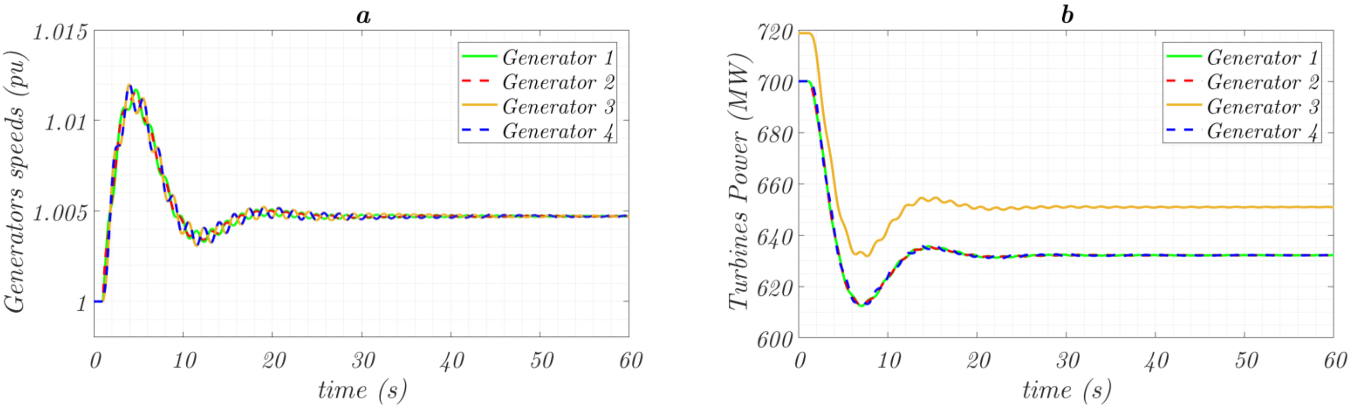

Figure 4. Generators speeds and turbines power responses of the original benchmark system [1] under the Load A1 (cf. Figure 1) disconnection event.

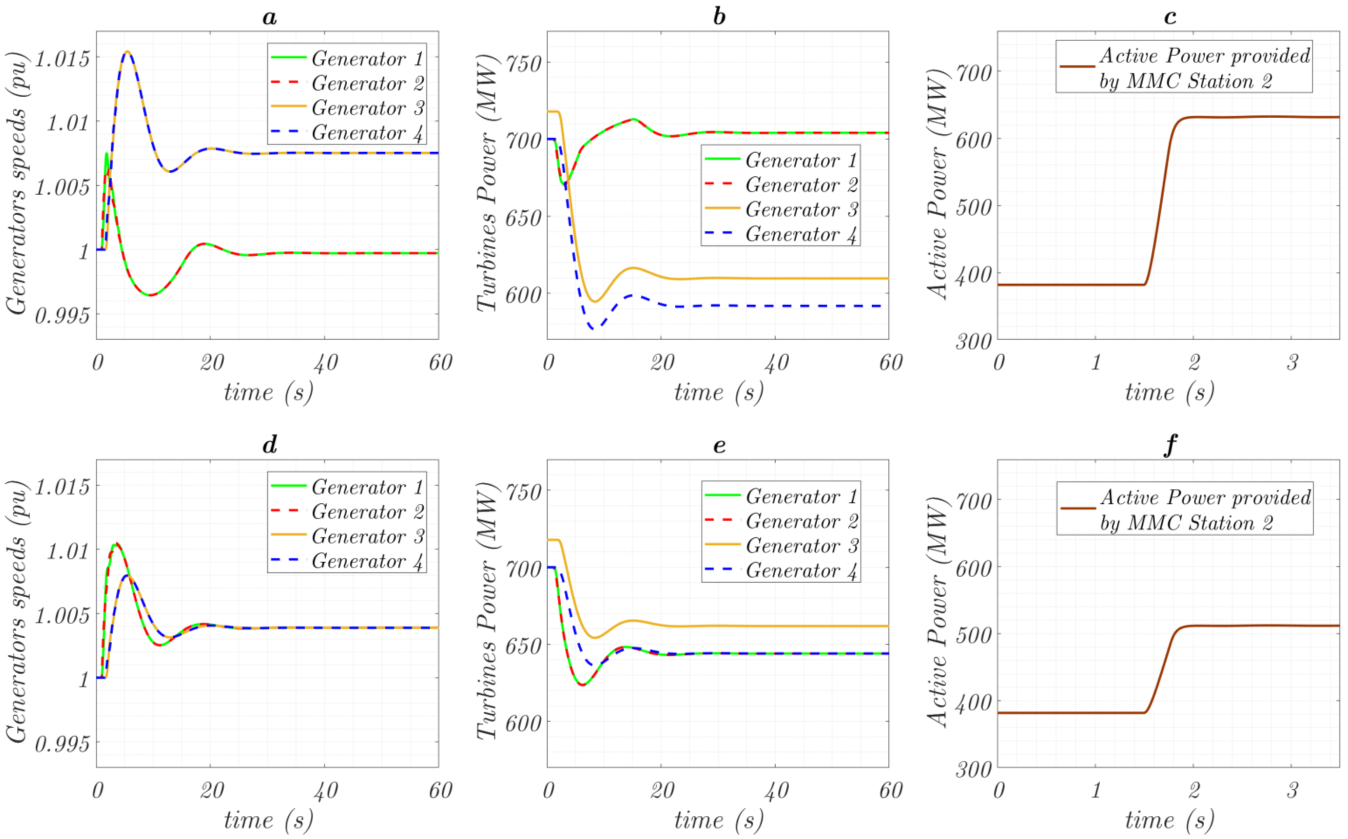

Figure 5. 5a shows the generators' speeds and Figure 5b shows the turbines power responses of Figure 1 when APG = 1 GW/s and ΔP = 250MW values (Figure 5c) are used by the VSC-HVDC system to mitigate the frequency deviation produced by the disconnection of Load A1. Figure 5d shows the generators' speeds and Figure 5e shows the turbines' power responses of Figure 1 when the (MVMO based) optimized values of APG and ΔP (Figure 5f) are used to mitigate the frequency deviation produced by disconnection of the Load A1.

station. This is done, in order to attempt to quickly mitigate the frequency excursions occurring in the AC network connected to the AC side of the corresponding VSC station. Consequently, Figure 5a and Figure 5b show the dynamic response of the system shown in Figure 1 (i.e. AC tie-lines of the original system replaced by a VSC-HVDC system) when the Load A1 is disconnected. In this case, the generators' speeds and mechanical powers responses were obtained by setting (as shown in Figure 5c), the ΔP value to 250 MW and the APG value to 60 GW/min (or 1 GW/s) which is a typical adjustment used during emergency power conditions [2].

It can be seen that by utilizing these adjustments, the generators' rotor speeds deviations (peak value and steady-state) belonging to the AC network B result comparatively higher than the ones shown in Figure 4a. In terms of the mechanical power associated to the generators from AC network B (Figure 5b), the steady-state deviation also results comparatively higher, when it is compared against the mechanical powers presented in Figure 4b.

B.3 System response (with the AC tie-lines replaced by the VSC-HVDC link) with optimized APG and ΔP values.

Following the activation criteria for the frequency support strategy mentioned in section 4.b.2, the optimal ΔP and APG values were found by executing the algorithmic procedure shown in Figure 3. Figure 6 shows the fast convergence achieved by using the modified version of MVMO, whereas Figure 7 shows the evolution of the optimization variables over the function evaluations performed by MVMO. Note in Figures 6 and 7 that optimal values of (3), i.e. the ΔP and the APG (which minimize the objective function defined in (1)), were found in approximately 70 iterations. Furthermore, Figure 7 shows that the MVMO can find very quickly the lowest necessary value of ΔP while at the same time the APG value is not necessarily as highest but it is sufficient enough to minimize the objective function.

The optimal values of ΔP and APG are 134.15 MW and 28616 MW/min (or 477 MW/s), respectively. The dynamic responses shown in Figures 5d and 5e, as well as the corresponding VSC-HVDC active power adjustment shown in Figure 5f, indicate that the simultaneous optimization of ΔP and the APG result in reducing the peak and post-disturbance steady-state value of the generators' rotor speed (i.e. the frequency performance of the system) while contributing to damp out the inter-area oscillations. This is attributed to the fact that the space-time (or instantaneous) vector control based VSC-HVDC system alters the interplay between the AC networks (i.e. modified electromagnetic linkage interaction between the synchronous generators in each AC network). Additionally, considering that the optimization carried out by using MVMO changes the APG value, it can be considered that the MVMO-based tuning of the frequency support strategy for VSC-HVDC systems constitutes an emergency (fast) active power-frequency support method for VSC-HVDC systems.

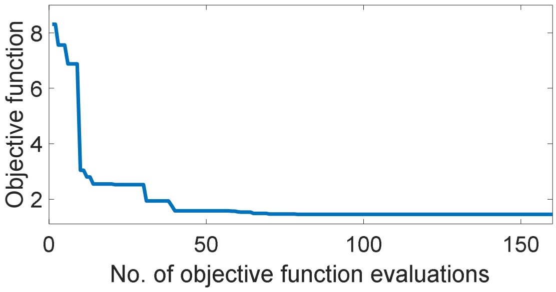

Figure 6. Convergence of MVMO.

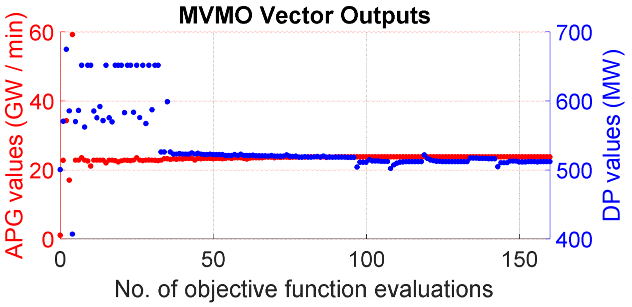

Figure 7. Evolution of optimization variables.

V. CONCLUSIONS

This paper presented an MVMO based approach for optimal tuning of the active power deviation (ΔP) and the active power gradient (APG) parameters of the control system for frequency support provided by a VSC-HVDC system. MVMO was modified to use LHS instead of random sampling. In this way, MVMO covers the whole search space more uniformly, and as shown by numerical results, this resulted in a fast convergence (optimal values of the ΔP and the APG found in around 1000 function evaluations). The optimal values of ΔP and the APG determined by using MVMO caused the VSC-HVDC to provide a small amount of extra active power injection with a very pronounced gradient on the AC side in which a power imbalance occurs. This helped to reduce the frequency peak, the post-disturbance steady-state value of frequency, as well as to improve the damping of inter-area oscillations. The MVMO-based approach will be applied to a multi-terminal HVDC system. The results of this ongoing research will be shown in a future publication. Statistical tests on the performance of MVMO and a comparative assessment against other heuristic optimization methods is being investigated and will be presented in a future publication.

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