Virtual Synchronous Generator Control of Multi-port Autonomous Reconfigurable Solar Plants (MARS)

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***Abstract*—Multi-port autonomous reconfigurable solar power plant (MARS) is an integrated concept for integration of solar photovoltaic (PV) and energy storage systems (ESS) to transmission alternating current (ac) grid and high-voltage direct current (HVdc) links. The integrated development incorporates advanced control methods to provide enhanced grid ancillary services such as fast frequency responses and dynamic voltage support. In this paper, the virtual synchronous generator (VSG) control algorithm of MARS is discussed. The proposed VSG-based control enables enhanced synthetic inertial response and flexible frequency response characteristics of hybrid PV and ESS power plants in accordance with grid ancillary service requirements. Multi-port power electronics interface allows controlled emergency power support from MARS to local transmission ac grid and remote grid through the HVdc link. The performance of VSG control is validated using a reduced-order model of MARS in Simulink. Methods for estimating grid ancillary service capabilities of MARS are also discussed.**

***Index Terms*—Hybrid PV power plant, multi-port power electronics, virtual synchronous generator (VSG), inertial response, fast frequency response, grid ancillary services.**

I. INTRODUCTION

As the penetration of solar PV generation rises and battery prices continue to decline, on-site storage has become an economic choice in utility-scale solar photovoltaic (PV) power plants. Hybrid PV and storage power plants can operate with similar dispatch characteristics as conventional power plants, participating in energy markets and providing grid ancillary services such as frequency responses and dynamic voltage support [1,2]. Large-scale solar PV and wind power plants or generation systems are located in the sites with high solar irradiance and high wind speed, respectively. These sites typically are remote from the load centers or the bulk transmission network. The local transmission grid areas are typically weak and have various power delivery constraints. Grid integration often requires long distance and high-capacity transmission lines, such as extra high voltage (EHV) alternating current (ac) lines and high-voltage direct current (HVdc) links. Recent system studies have shown potential economic benefit of HVdc links over ac transmission expansion options [3]. Multi-port autonomous reconfigurable solar plant (MARS) is an integrated concept for integration of hybrid PV and energy storage system (ESS) power plants to transmission ac grid and HVdc link [4]. The circuit architecture of MARS is shown in Fig. 1, which consists of 3 phase-legs connecting to the transmission ac grid and the HVdc link. Each phase-leg is comprised of 2 arms: upper and lower arms. Each arm comprises series-connected submodules (SMs). The normal SMs are based on half-bridges, which are also the front-end of PV and ESS SMs. The PV systems in the PV-SMs are connected to the front-end through a unidirectional dc-dc converter. The ESS systems in the ESS-SMs are connected to the front-end through a bidirectional dc-dc converter.

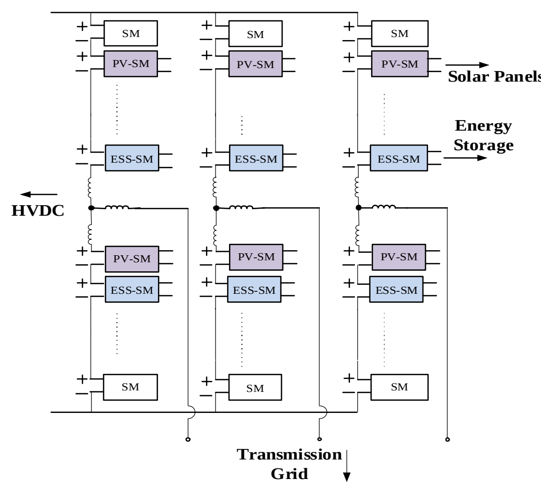

Figure 1**:** MARS circuit architecture [4]

One of the greater concerns with increased penetration of inverter-based resources (IBR) in power grid is reduction in the grid's capability to recover from severe frequency or voltage disturbances [3,5]. The integrated development of MARS incorporates advanced control methods to enable flexible plant operational performance and enhanced grid ancillary services (A/S). The proposed VSG-based control of MARS that enables enhanced synthetic inertial response and flexible frequency response characteristics of hybrid PV and ESS power plants is presented in this paper. The paper is organized as follows: The control architecture of MARS is briefly discussed in Section II. The VSG-based control of

MARS for grid frequency support is described in Section III. Simulation results using a reduced order model of MARS to evaluate the VSG-based control are presented in section IV. The methods for estimating grid ancillary service capabilities of MARS are discussed in Section V. Conclusions and future research work are provided in Section VI.

II. CONTROL ARCHITECTURE OF MARS

The hierarchal control architecture of MARS that consists of three control layers: L-1 controller, L-2 controller, and L-3 controller [4] is shown in Fig. 2.

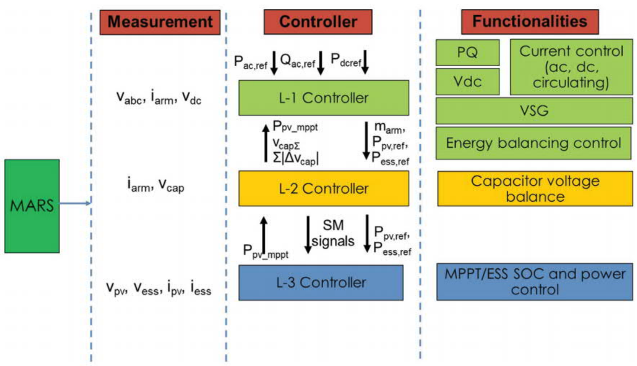

Figure 2: MARS control architecture [4]

The L-1 controller is the plant level controller (PLC). The PLC receives power order commands from the system operator that may include power transferred to ac grid ($P_{ac,ref}$), power transferred to HVDC link ($P_{dc,ref}$), and reactive power provided to ac grid ($Q_{ac,ref}$). It maintains the power dispatched from the integrated system, controls dc voltage and ac/dc currents, and provides energy balancing between different types of SMs. The PLC determines the internal reference power commands of PV and ESS SMs based on the power order commands and the PV and ESS operating parameters. The frequency support and voltage support to the power grid is provided through the VSG control, which is explained in the next section. The energy balancing control generates the reference circulating current within the phase legs, and the determined modulation indices of each arm, reference PV power and reference ESS power are sent to the L-2 controller. The L-2 controller basically maintains the capacitor voltages in the SMs and generates the switching signals for the front-end half-bridges of all the SMs. The L-3 controller controls the power from PV and ESS SMs, controls the dc-dc converter currents, and sends the switching commands to the dc-dc converters.

III. VSG-BASED CONTROL OF MARS

A. *VSG control overview*

Low levels of rotational inertia in a power system, caused by high shares of inverter-based resources have implications on the grid's frequency dynamics. There are increased concerns on large frequency deviations and potential risk of system instability [3,5]. VSG control methods have been broadly investigated for enabling fast frequency response of inverter-based resources [6,7]. The choice of VSG control method depends on the application and the desired level of replication of the dynamics of the synchronous generators. Synchronous generator model (SGM) and swing equation (SWE) based methods are suitable, traditionally, in isolated power systems such as microgrids as they can operate autonomously as grid forming units. Frequency-power response (FPR) based method behaves like a grid following unit with added inertial response capability and is applicable for interconnected operations (with sufficient presence of traditional synchronous generators). In recent years, grid-forming converter concepts have been extended for use in interconnected power systems and considered as promising technologies for stable power grid operation under high shares of renewables [8,9].

B. *VSG-based control of MARS*

The FPR-based VSG control method is chosen for implementation in the PLC of MARS. Basically, the active power output of the FPR-based VSG control in response to a frequency disturbance in the power grid can be expressed as:

$$P_{VSG} = K_D \Delta f + K_I \frac{d\Delta f}{dt}$$

where, Δf and dΔf/dt represent the frequency deviation and the corresponding rate of change of frequency (ROCOF). K_D and K_I are the frequency droop response (FDR) and the synthetic inertial response (SIR) constants.

The VSG control algorithm of MARS is shown in Fig. 3. The frequency response is activated when system frequency deviation (F_{Dev}) or frequency derivative (ROCOF) meets their respective preset dead band (DB). The SIR and the FDR are constrained by the available frequency response capabilities (FRC) of MARS that are explained in the next subsection.

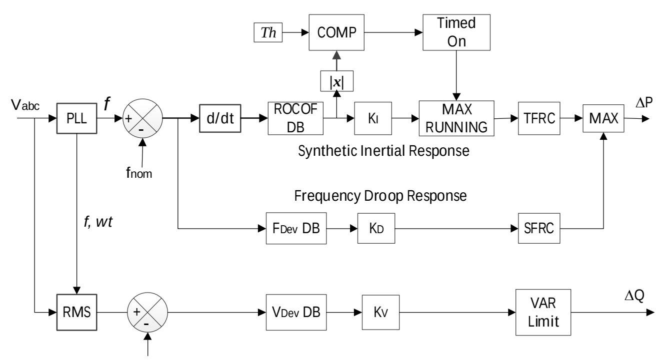

Figure 3: VSG control algorithm of MARS

To enhance the effect of fast frequency response of MARS, a control feature is added in the SIR control loop to hold the maximum power output of the SIR for a preset time period, say 5-10 seconds. Sustained SIR of inverter-based resources is desirable and might be required in future power systems with high renewables penetration for enhancing frequency stability [10]. The MAX Running block will output the maximum of all past SIR till being reset by the Timed-On delay block. ds. Voltage supervision is added in the VSG controller to interlock the frequency responses of MARS if abnormal voltages are detected at MARS ac terminals. This interlock scheme is used to avoid unwanted responses of MARS to transient frequency disturbances in the grid induced by network faults.

C. *FRC limits of MARS*

The FRC limits of MARS are described in Fig. 4. In normal operating conditions, the PV system may operate at MPPT (maximum power point tracking) mode or non-MPPT mode, while the ESS system may operate at charging, discharging or standby mode. The FRC limits of MARS include transient frequency response capability (TFRC), short-term frequency response capability (SFRC), and long-term frequency response capability (LFRC). These limits are determined by aggregated PV and ESS operation parameters and designed overload capability of energy storage. For example, the PV system may operate at non-MPPT mode with 10-15% of reserved headroom for grid frequency regulation. The ESS may have three overload specifications: 200% for several seconds, 150% for 30 seconds, 120% for several minutes [11].

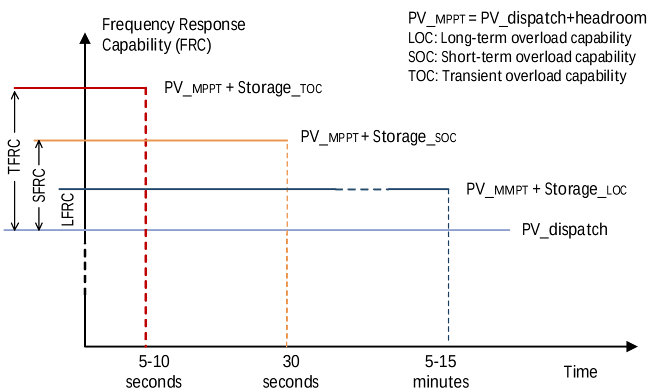

Figure 4: Frequency response capability of MARS

D. *Fast power flow control of HVdc link*

For gigawatt scale hybrid PV and storage power plants, fast frequency response may result in a step-like power injection, in the magnitude of several hundred megawatts, into the power grid. This may cause unacceptable disturbance in the local transmission grid and potential risk of instability. The VSG-based control of MARS includes an emergency power support allocation scheme with which the incremental power output resulting from frequency responses can be injected into the local ac grid area and the remote grid area through the HVdc link according to preset proportions subject to the interface rating constraints.

IV. Simulation Results and Verification

A. *Test system decription*

In this section, a case-study is presented that showcases the performance of the VSG-based control (with enhancements) of MARS for grid frequency support. The test system is based on the proposed MARS system that can be developed in Pittsburg, California. The scope of the proposed MARS system is to integrate hybrid PV and ESS with the HVdc station of the Trans Bay Cable (TBC) link at Pittsburg [4]. The rated capacity of PV system is 102 MW and the rated battery storage capacity is 33 MW/110 MWh. The test system setup is shown in Fig. 5, which consists of a reduced-order model of MARS, a frequency-controlled voltage source, and equivalent local transmission ac network [12].

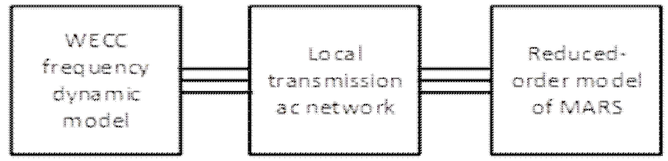

Figure 5: Test system setup in Simulink

The reduced-order model of MARS is the equivalent model of system hardware and PLC. In this case study, the dynamics of HVdc link is not the focus and thus the dc output of MARS is connected to a dc source. The local ac transmission network is modeled by equivalent circuits between the MARS location and the bulk power system. The bulk power system is a transfer function-based frequency dynamics model which can adequately represent the frequency dynamics during losses of generations in western electric coordinating council (WECC) grid [13]. With proper parameters, the WECC frequency dynamics under reduced inertia and different generation outages can be emulated. Reduced short circuit ratios at the MARS location can be realized by varying the line parameters of local transmission grid. The test system is implemented in Simulink. In this section, we only present the simulation results relevant to the frequency response performance of the VSG-based control (with enhancements).

B. *Enhanced SIR of MARS*

The SIR of MARS during loss of 804 MW generation in the WECC system is shown in Fig. 6. In this test case, the PV system is capable of producing the rated power 102 MW, but MARS operates at standby mode meaning no power injection into the grid. The ESS may be charged by PV generation. Thus, MARS has total of 135 MW reserved capacity available for grid frequency support.

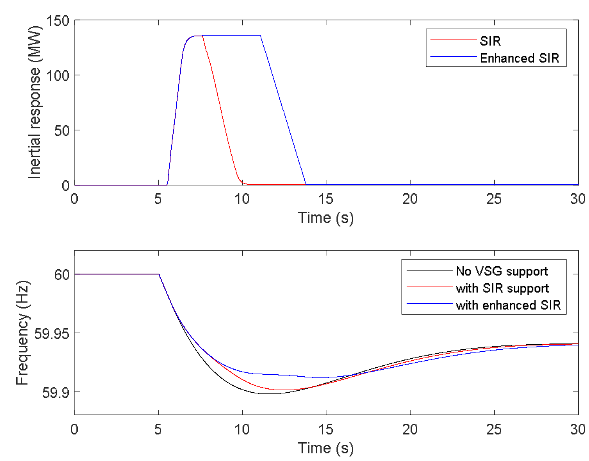

Figure 6: Enhanced SIR of MARS

As shown in Fig. 6, typical SIR control methods basically mimic synchronous machine inertia, that is, the inertial response is proportional to ROCOF shown as the red curve. It increases quickly after the disturbance, and then it decreases gradually as ROCOF decreases. When the system frequency reaches its nadir, the inertial response equals to zero. With the enhanced SIR control, the maximum output of SIR is held for 5 seconds shown as the blue curve. It can be observed that sustained SIR is beneficial for increasing system frequency nadir.

C. Flexiblilty of VSG control of MARS

The SIR and the FDR of MARS can be configured by proper control parameter settings. Depending on grid A/S requirements, MARS may provide either SIR or FDR or both frequency response services to the grid. As shown in Fig. 7, the desired frequency responses can be configured in accordance with the grid A/S requirements in high renewable power systems [10]. The emergency power output of MARS can be injected into the local tranmsission grid and the HVdc link in preset proportions, as shown in Fig 8.

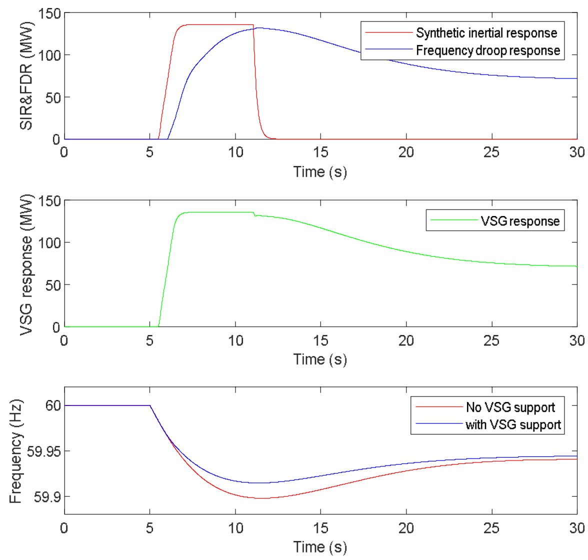

Figure 7: Configurable frequency responses of MARS

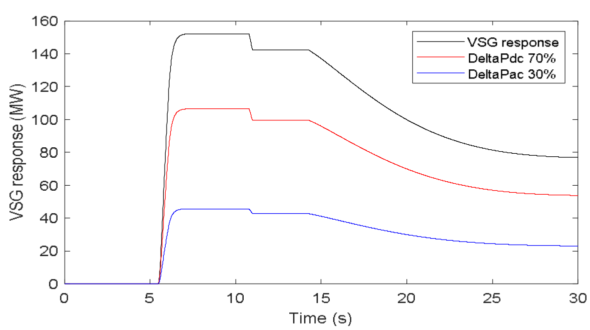

Figure 8: Fast dc link power flow control

D. TFRC and SFRC of MARS

The SIR and the FDR of MARS can be enhanced utilizing the designed transient overload capability and short-term overload capability of the multi-port power electronics. A test case with enhanced frequency response of MARS, wherein the ESS can be overloaded 150% for 5 seconds and 120% for several minutes, is shown in Fig. 9. It is assumed that the PV generation system operates at non-MPPT mode with 20 MW reserved headroom and the ESS operates at standby mode. Slightly improved system frequency improvement can be observed when designed overload capabilities are utilized.

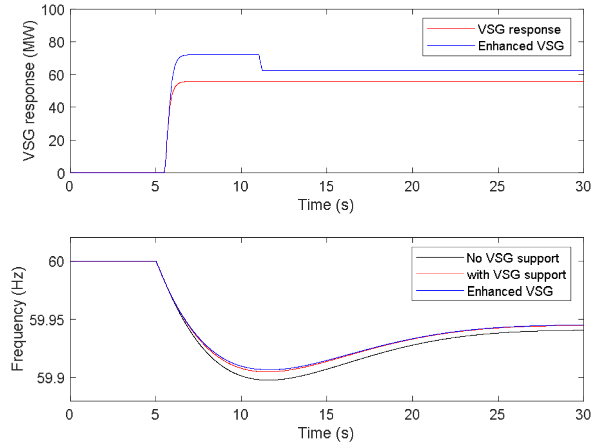

Figure 9: Enhanced frequency responses of MARS

V. ANCILARY SERVICES OF MARS

A. Scheduling and dispatch of MARS

MARS can participate in both wholesale energy markets and grid A/S markets. In day-ahead markets, MARS can submit its next day economic bids or self-schedule bids to the system operator based on day ahead market price and solar forecasts. Qualified A/S capabilities of MARS include regulation up and regulation down, spinning reserve, primary frequency response, and SIR. In the day-ahead A/S markets, the system operator determines the requirements for different types of A/S and typically procure the needed A/S from qualified providers. In the next day operations, MARS optimizes the plant internal dispatch to deliver the committed firm capacity to the grid and regulates its real-time power output in response to automatic generation control (AGC) signals. MARS can provide the committed fast frequency responses to the grid under disturbances.

B. A/S capabilities of MARS

The available A/S capability of MARS is dependent on the operation modes of the plant. PV system may operate at MPPT, non-MPPT, or standby mode; and ESS may operate at charging, discharging, or standby mode. The optimized hourly operation profiles of MARS at Pittsburg for two successive typical high solar insolation days is shown in Fig. 10. In the shown hourly MARS operation profiles, the PV generation system operates at MPPT mode while the ESS operations (charging and discharging) are optimized based on the energy market prices and subject to the maximum and minimum storage limits. Hourly A/S capabilities of MARS for next day A/S markets can be estimated based on the optimized hourly operation profiles. The estimated A/S capabilities of MARS at Pittsburg for the two successive high solar insolation days are shown in Fig. 11. Storage limits are enforced for estimating A/S capabilities with maximum and minimum limits set at 80% and 20% of rated MWh capacity respectively. This will allow the ESS to compensate the fluctuated output and reduce the ramping rate of PV generation while maintaining the committed A/S capabilities. It also improves the lifetime of the battery in ESS.

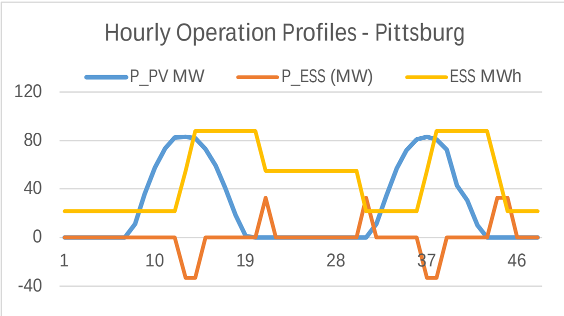

Figure 10: Optimized hourly dispatch profiles of MARS

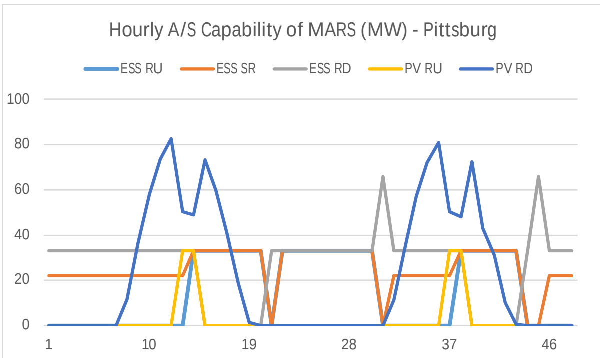

Figure 11: Estimated hourly A/S capabilities of MARS

The methods for estimating hourly A/S capabilities of MARS are described below.

- ESS_RU (Regulation Up of ESS) = min (current stored energy – min storage limit, rated ESS MW – scheduled discharge)
- ESS_RD (Regulation Down of ESS) = min (max storage limit – current stored energy, rated ESS MW) + scheduled discharge
- ESS_SR (Spinning Reserve of ESS) = min (current stored energy, rated MW – scheduled discharge)
- PV_RU (Regulation Up of PV) = scheduled charge power to ESS + headroom
- PV_RD (Regulation Down of PV) = footroom from the scheduled PV generation
- PV_SR (Spinning Reserve of PV) = PV_RU

MARS capabilities for fast frequency response services can be estimated using the similar methods for the regulation up services. In principle, the regulation up capability of MARS is qualified for fast frequency response services. As discussed earlier, the frequency responses of MARS could be enhanced by utilizing the designed transient and short-term overload capabilities of ESS. Provision of fast frequency response services would not affect the regulation up or spinning reserve services of MARS because these services are needed at different system conditions and require different response times and effective durations.

VI. Conclusions

This paper presents an enhanced virtual synchronous generator (VSG) control algorithm of MARS to provide fast frequency response services to the power grid under severe frequency disturbances. The proposed VSG-based control has several features that enable enhanced synthetic inertial response, effective utilization of frequency response capabilities, and flexible response characteristics in accordance with grid ancillary service requirements. The performance of the proposed VSG control algorithm is verified in the reduced-order model of MARS together with equivalent bulk power system and local ac network models in Simulink. Methods for estimating the A/S capabilities of MARS are also discussed. Provision of fast frequency response services from MARS will not affect its committed regulation up or spinning reserve services since these services require different response times and effective durations.

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