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Discrete and Integrated Solutions for Hybrid PV Plants Without Momentary Cessation in Low SCR and High Penetration PE Grids

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***Abstract*—With the increased penetration of power electronic (PE) based loads and sources, advanced solutions may be required for the enhancement of grid stability in regions with low short circuit ratio (SCR) and high penetration PE grids. The requirement of advanced solutions arises from the gradual paradigm shift of the electric grid from the traditional electric machine dominant system to a high penetration of PE-based system. One of the major challenges with such systems in recent times is the momentary cessation during alternating current (ac) grid transmission faults. During momentary cessation, PE-based resources cease to operate, thus creating probable reliability challenges for the grid. In this paper, potential feasible options to provide continuity of operation during such scenarios are presented. The options are considered through identifying upgrades in existing and upcoming discrete development of photovoltaic (PV) and energy storage systems (ESS) termed as discrete hybrid PV plants. Additionally, an advanced concept of integrated development of PV and ESS connecting to ac transmission grid links called multi-port autonomous reconfigurable solar power plant (MARS) is evaluated. The developed new solutions are evaluated for different grid use cases and scenarios in PSCAD.**

***Index Terms*—Discrete PV and ESS, synchronous condenser, low SCR, multi-port, MARS**

I. INTRODUCTION

There has been a significant drop in the levelized cost of electricity (LCOE) of utility-scale photovoltaic (PV) power plants in the United States in the past decade. These economic benefits have led to rapid increase in PV power plants. In addition to the increased interest in PV power plants, utilities are mandating increased energy storage system (ESS) installations. This proliferation of PV power plants and ESS in power grids is resulting in the following two major changes: a) high penetration of power electronic (PE) based resources in power grids; b) retirement of synchronous generators. These high penetration PE grids are significantly low in short circuit strength and are characterized by low short circuit ratio (SCR). The reason for the low short circuit strength in high penetration PE grids is due to their inability to provide higher short-circuit current unlike their counterparts: synchronous generating resources. Interconnection of PE-based resources to such low SCR grids might manifest unforeseen issues ranging from voltage instabilities to control instabilities. One such issue observed is momentary cessation in PV plants [1].

During transmission line faults, several utility-scale state-of-the-art PV plants momentarily cease to operate [2]. This phenomenon may be detrimental to the stability of the power grid. Several events in the power grid in California led to widespread loss of PV generation in 2016-2020, with momentary cessation utilized in PE-based resources being one of the causes for the loss [1], [3]. Based on these events, some of the recommendations for integration of future PE-based resources include: a) the use of momentary cessation should be as infrequent as possible; b) the maximum amount of active power (P_{poi}) and reactive power (Q_{poi}) that PE-based resources can provide during a transmission line fault should be utilized; c) PE-based resources should not trip within the "no trip zone" defined in the PRC-024-2 standard [4]; and d) studies are needed that employ detailed electromagnetic transient (EMT) models [5].

Very few studies have been performed on momentary cessation and its effects on transmission system stability in future

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power grids characterized by low SCR and inertia [6]–[10]. In [6]–[8], the effects of momentary cessation on power system transient stability are studied. Furthermore, in [8] the solution to momentary cessation was provided for a case of strong grid scenario. In [9], an inverter model including momentary cessation during balanced three-phase faults is developed in PSS/e. In [10], suggestions to minimize momentary cessation based on acquired field experiences from PV plant and Type III and Type IV wind generator responses under transmission line system faults are presented. These aforementioned studies either assume momentary cessation of inverter-based resources during grid voltage disturbances or provide voltage stability for the systems connected to strong grids rather than providing solutions for continuity of operation during abnormal grid conditions in weak grid scenarios. On the contrary, solutions to provide continuity of operation (without momentary cessation) during different transmission line faults in state-of-the-art hybrid discrete PV plants connected to low SCR and low inertia grids are proposed in this research work. These types of plants will need additional upgrades to ensure continuity of operation under faults [11]. Additional upgrades may include combination of synchronous condensers, shunt capacitor banks, and dampers in hybrid PV plants. Alternatively, PV and ESS that can connect to high-voltage direct current (HVdc) and/or high-voltage alternating current transmission grids may also be considered [12]. This leads to the discrete development of PV inverters, ESS inverters, associated upgrades, and several transformers in future grids with a high penetration of renewables.

Reducing momentary cessation or trips in discrete hybrid PV plants arising from control interactions and/or transmission line faults is one of the challenges that needs to be resolved [1]. In addition to considering upgrades in discrete hybrid PV plants that can reduce or eliminate momentary cessation, new solutions such as the integrated development of PV and ESS connecting to high-voltage alternating current (ac) transmission grid links through multi-port autonomous reconfigurable solar power plants (MARS) may also be considered [13]. The MARS system solution, which has been shown to provide continuity of operations under transmission line faults [13], is also evaluated in this paper.

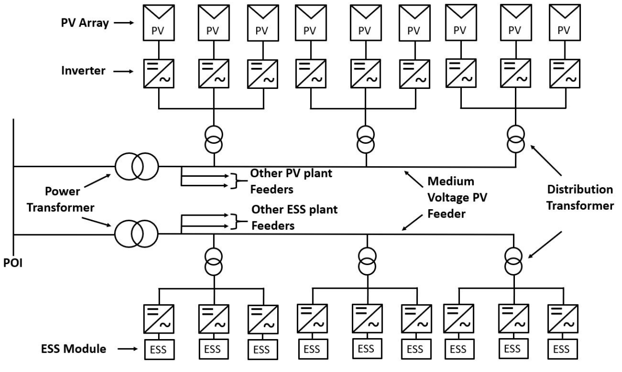

Fig. 1. Generic layout of discrete hybrid PV plant

II. OPTIONS TO REDUCE MOMENTARY CESSATION

State-of-the-art utility-scale discrete hybrid PV plants are large generation systems that are connected to the high-voltage ac transmission grid. These discrete large hybrid PV plants have multiple medium-voltage radial feeders. They include many components such as PV arrays, ESS systems, cooling systems, and transmission substation apparatus (power transformers and circuit breakers). The generic layout of a discrete hybrid PV plant is shown in Fig. 1.

A. Discrete Hybrid PV Plant

a) Large Scale Discrete Hybrid PV Plant: The PV plants in discrete hybrid PV plant are modeled as an aggregation of multiple inverters, distribution lines, and transformers into one equivalent system in PSCAD. The equivalent model consists of a PV array, a boost converter, an inverter, filter, transformer, and scaling component. Additionally, there are three controllers: dc-dc converter controller, inverter controller, and power plant controller. The dc-dc converter controller controls the dc link voltage and inherently the PV power transferred. The inverter controller controls the active power and reactive power based on dispatched commands from the power plant controller. Furthermore, based on the ac-side disturbances the inverter may provide additional reactive power and active power support during faults. The power plant controller identifies ride-through requirements and introduces voltage support at the point of interconnection (POI) of the PV plant. A scaling component is used to model several units of inverters and distribution lines/transformers in the PV plants [14]. The ESS plants are also modeled based on an aggregated model that represents multiple inverters as a single inverter. The model consists of a battery, an inverter, filter, transformer, and scaling component. The scaling component is similar to that used in the PV plant in [14].

b) Discrete Hybrid PV Plant Control: The inverter units in the discrete hybrid PV plant employ cascaded two-loop current-mode control strategy in dq frame of reference. The active power and reactive power are controlled through the outer-loop proportional integral (PI) compensators and the filter currents are controlled through the inner-loop PI compensators. The outer-loop PI compensators get the power reference commands from the power plant controller and feedback signals from the inverter terminals. Based on these reference commands and feedback signals, the outer-loop PI compensators generate the reference commands for the filter current inner-loops. These filter current inner-loops then generate the voltage references in dq frame of reference based on the reference commands and feedback signals. The generated voltage references in dq frame are converted to abc frame of reference that is termed as modulation index. As a final step, the reference commands for phase voltages in abc frame of reference (modulation indices) are used to generate the firing pulses that are fed to the switches in the inverter units.

B. MARS

a) MARS System Architecture: The architecture of the MARS system is shown in Fig. 2. The MARS system is a

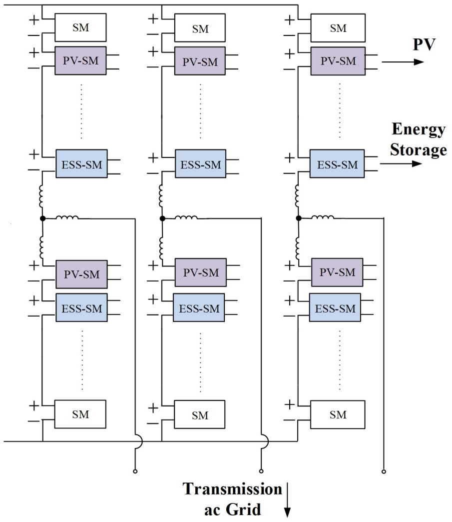

Fig. 2. Overview of the MARS system architecture

three-phase system with six arms in total. Each arm consists of normal sub-modules (SMs), PV, and ESS SMs. The SMs are capacitor connected front-end half-bridge circuits. The normal SMs include only front-end half-bridge SMs. The PV systems in each PV SM are connected to the front-end half-bridge through either isolated or non-isolated dc-dc converters. The ESS in each ESS SM are connected through a bidirectional dc-dc converter to the front-end half-bridge. The detailed modeling of MARS and the corresponding simulation algorithm applied for fast simulation are described in [13], [15].

b) MARS Control System: The control architecture in the MARS system is hierarchical in nature. It consists of the following functionalities: (a) voltage and frequency support to the ac grid, active and reactive power control, dc link voltage control, current control (ac current control, dc current control, and circulating current control), and energy balancing control in the L1 controller; (b) capacitor voltage balancing control in the L2 controller; and (c) PV and ESS SMs power and current control in the L3 controller [13]. The detailed implementation of the entire control architecture of the MARS system are described in [13].

III. PLANT INFORMATION AND UPGRADE NEEDS

In this study, the following plants are studied: (a) discrete hybrid PV plants with and without controller upgrades; and (b) a MARS system. These plants are connected to Western Interconnection (WI) grid with low SCR of 2 at Victorville, California. The WI grid is modeled based on the data-driven approach [16].

A. MARS Plant at Victorville

The number of each type of SMs required in the MARS plant at Victorville, California is tabulated in Table I. The total number of SMs per arm is determined by the dc-link voltage at the location. In this case, there are total 2400 SMs in the MARS plant.

TABLE I
VICTORVILLE MARS SYSTEM PARAMETERS

Parameter	Value
System rating	2000 MW
dc bus voltage (V_{dc})	±525 kV
ac side voltage (V_{ac})	500 kV
PV system power rating (P_{PV})	1000 MW
ESS system power rating (P_{ESS})	389.8 MW
Number of normal SMs per arm (N_{norm})	111
Number of PV SMs per arm (N_{PV})	208
Number of ESS SMs per arm (N_{ESS})	81
Total number of SMs per arm (N)	400
Arm inductance (L_{o})	90.0 mH
Arm resistance (R_{o})	0.1 Ω
Grid side inductance (L_{s})	40.0 mH
Grid side resistance (R_{s})	0.83333 Ω
SM capacitor voltage (V$_{SM}$)	2.625 kV
SM capacitance	20.0 mF

B. Discrete Hybrid PV Plant

The PV plant in the state-of-the-art discrete hybrid PV plant is rated at 1000 MW (for a large plant) and is connected to a power transformer of 33 kV/500kV (based on typical voltages). The 500 kV side of the power transformer is connected to the WI grid. The ESS plant is rated 389.8 MW. Each inverter unit in the discrete hybrid PV plant is rated 800 kW. There are 1248 inverter units in the PV plant of the discrete hybrid PV plant. Each of the 486 inverter units in the ESS plant are also rated 800 kW.

C. Upgrades in the Discrete Hybrid PV Plant

The upgrades introduced in the state-of-the-art discrete hybrid PV plant include synchronous condensers (SC), shunt capacitors, and dampers re-sized to ensure stable operation of plant with lower harmonics.

D. SCs to Increase SCR

In the scenarios of a high penetration of PE-based systems and a low traditional synchronous machine resource based system, the ac grid short circuit strength might be quite low. This inadequacy in providing sufficient short circuit strength may lead to stability problems while connecting newer PE-based systems. One of the potential solutions to such problems is installing SCs in the system. Therefore, SCs are installed as an “upgrade” in the ac grid to ensure stable operation of the discrete hybrid PV plant. The objective of installing SCs in the low SCR grids along with these plants is to increase the SCR of the grid. Thus, improving the stability and transient performance of the plants connected to the low SCR grids.

a) Selection of SCs Rating: The SC installed in the ac grid is modeled based on a GENROU synchronous machine model with an IEEE Type-1 excitation system model. There is no governor attached to the turbine of the machine. The SCs are installed on the low voltage side of a power transformer. The dynamic parameters of the GENROU model are based on typical values of synchronous machines. The rating and the dynamic parameters of the SCs are tabulated in Table II. The selection of SC ratings is based on the design studies performed for stable operation of discrete hybrid PV plants. In these studies, the total SC rating is varied proportional to

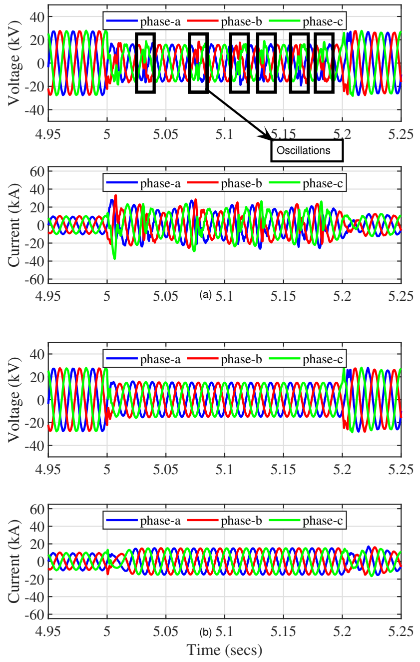

Fig. 3. POI instantaneous grid voltages and currents comparison (a) before and; (b) after inverter control upgrades

TABLE II
PARAMETERS OF SCs

Parameter	Value
Total SC rating (Without inverter control upgrades)	3500 MVA
Total SC rating (With inverter control upgrades)	1400 MVA
Rated RMS voltage (LL)	20 kV
Inertia constant (H)	4.1214 MW.s/MVA
Damping (D)	1.0 p.u.

the discrete hybrid PV plant rating. Simulation studies are performed in the PSCAD environment for SC ratings of 700 MVA (0.5x the discrete hybrid PV plant rating), 1400 MVA (1x the discrete hybrid PV plant rating), 2100 MVA (1.5x the discrete hybrid PV plant rating), 2800 MVA (2x the discrete hybrid PV plant rating), and 3500 MVA (2.5x the discrete hybrid PV plant rating).

E. Control Upgrade in the Discrete Hybrid PV Plant

Without the inverter control upgrade, for the SC ratings of 700 MVA - 2800 MVA, oscillations were observed in the POI instantaneous grid voltages and currents during the three-phase fault conditions. This was due to the fact that inverter control in the discrete hybrid PV plant was operated in the higher modulation index region of 0.8 - 1.15 as per the current state-of-the-art implementation. With the inverter control upgrade the discrete hybrid PV plant could provide stable voltage support with no oscillations for reduced SC rating. The upgrade in the inverter control is: operating inverter in lower modulation index region of 0.2 - 1.15. This controller upgrade in the discrete hybrid PV plant resulted in reduction of the required SC rating from 4900 MVA (3.5x) to 1400 MVA (1x) for its stable operation. The POI instantaneous grid voltages and currents comparison before and after inverter control upgrades for 1400 MVA SC during three-phase fault is

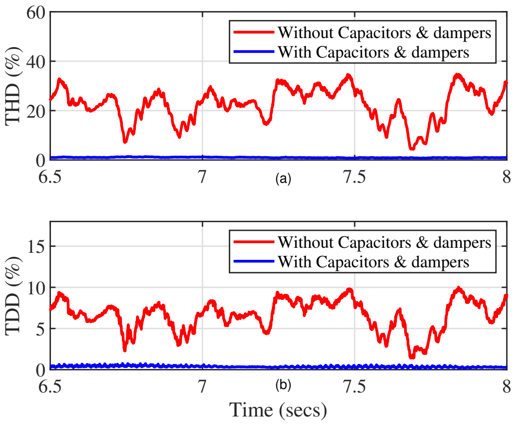

Fig. 4. a) THD on high-voltage side (500 kV) of hybrid PV plant; and b) TDD of grid currents on the high-voltage side (500 kV) of hybrid PV plant

shown in Fig. 3. From the figure, it is observed that with the control upgrades, there are no oscillations present during the three-phase fault, thus providing stable continuity of operation.

F. Shunt Capacitor Banks and Dampers to Reduce THD

In the MARS system, the total harmonic distortion (THD) on the high-voltage side (500 kV) is well within the recommended limits specified in IEEE 519-2014 [17]. The multi-level nature of the voltage generated helps with maintaining the THD below the prescribed limits. Hence, no additional capacitor banks and/or dampers are necessary in MARS. In contrast to the MARS systems, the THD of the high-voltage side of the hybrid PV plants is greater than the recommend limits specified in IEEE 519-2014 [17]. Therefore it is necessary to install shunt capacitor banks along with upgrading dampers in the hybrid PV plants to ensure that the THD of the plant is below the recommended limits.

The shunt capacitors are installed on the low-voltage side (33 kV) of the power transformer based on the guidelines described in [14]. The dampers are installed on the low-voltage side of the PV inverter transformer in the PV plants and on the low-voltage side of ESS inverter transformer [14] of the hybrid PV plant. The dampers are upgraded accordingly to ensure THD and TDD recommended limits of IEEE 519-2014 are met.

1) Hybrid PV Plant: The THD of the high-voltage side (500 kV) grid voltage of the hybrid PV plant is shown in Fig. 4a with and without shunt capacitors. It is observed that with the installation of 40 μF shunt capacitor banks on the low-voltage side (33 kV) of each of the power transformer in the PV and ESS plants and upgrading dampers on the low-voltage side of the distribution transformer, the THD reduces to 1.0% (average value) and the total demand distortion (TDD) of the grid current is reduced to 0.4% (i.e. within the recommended limits). Without installation of shunt capacitors and dampers, the THD is well above the recommended limits ($>>$ 2%). The THD of the grid voltages and TDD of the grid currents on the low-voltage side for hybrid PV plants are below the recommended limits with and without shunt capacitors and

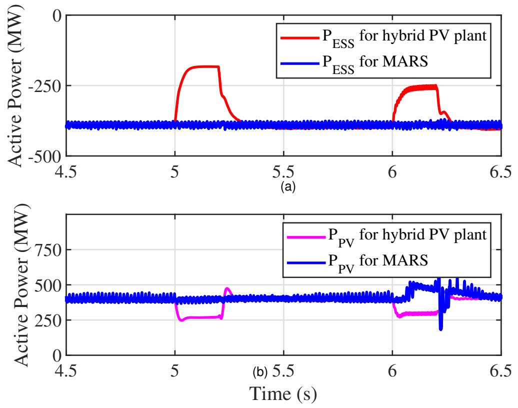

Fig. 5. Active power from MARS and discrete hybrid PV plant: a) PV systems; and b) ESS

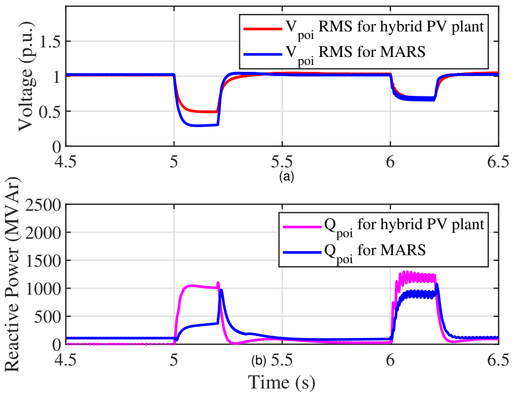

Fig. 6. POI RMS grid voltage (V_{poi}) and reactive power (Q_{poi}): a) MARS; and b) discrete hybrid PV plant

damper upgrades. The total demand distortion (TDD) of the grid current of the PV plant at the high-voltage side is shown in Fig. 4b. It is observed from Fig. 4 that the TDD is well above the recommended limits ($>> 2\%$) without the installation of shunt capacitors and dampers. It is observed from Fig. 4 that the TDD is reduced to 0.4% (i.e. within the recommended limits) with the installation of shunt capacitors and dampers. The THD of the grid voltages and TDD of the grid currents on the low-voltage side for hybrid PV plants are below the recommended limits with and without shunt capacitors and damper upgrades.

IV. EMT SIMULATION RESULTS

The main objective of this research study is to identify upgrades that enable discrete hybrid PV plant to provide stable transient performance as observed in MARS. The performance criteria is based on provision of continuity of operation that include uninterrupted service of operation and reactive power support during fault events in the transmission lines of the power grid. The PV and ESS power available to provide support during disturbances is kept the same in both the systems. The following two use cases are identified in this research study: (a) a balanced three-phase fault on the transmission line at t = 5.0 s; and (b) a line-to-line fault at t = 6.0 s. In these two use cases, the fault is self-cleared with a duration of 0.2 s. In this digest, these faults are evaluated for long distance fault scenario.

A. Discrete Hybrid PV Plant + Upgrades

The discrete hybrid PV plant is operating at a PV power dispatch P_{ac} of 390 MW. This power is used to charge ESS, with no net power provided to the grid from the PV-ESS system within the discrete hybrid PV plant. During the three-phase fault and line-to-line fault, the discrete hybrid PV plant alone failed to provide stable transient performance and continuity of operation (if operated without any additional ac upgrades and controller upgrades). With the installation of traditional ac upgrades and control upgrades, the discrete hybrid PV plant was able to provide continuity of service as well as operate with enhanced transient stability during the three-phase fault and line-to-line fault as shown in Fig. 5. It is observed from Fig. 5a and Fig. 5b that the power generated from the PV plant is used to charge the ESS plant during normal operating conditions. However, during the three-phase fault and line-to-line fault, the power generated by PV plant is reduced to 270 MW and 300 MW respectively and is not completely used to charge the ESS plant. From Fig. 6b, it is observed that in discrete hybrid PV plant, the Q_{poi} of 1000 MVAr and 1100 MVAr is provided by the PV and ESS plants during three-phase fault and line-to-line fault respectively. In the case of nearby faults, the discrete hybrid PV plant was not able to provide stable transient performance during the three-fault and line-to-line fault for the identified upgrades.

B. MARS

From Fig. 5, it is observed that in MARS, the total active power of 390 MW provided by the PV systems is utilized to charge the ESS of 390 MW rating during normal operating conditions. During the three-phase fault and line-to-line fault, the MARS plant is able to provide continuity of service as shown in Fig. 5 and Fig. 6 (without any additional upgrades). Furthermore, it is observed from Fig. 5, the active power provided by PV systems does not change during faults unlike the discrete hybrid PV systems. From Fig. 6b it is observed that the Q_{poi} support of 350 MVAr and 850 MVAr is provided by MARS during the three-phase fault and line-to-line fault respectively. For the nearby faults, MARS could provide stable continuity of operation without any upgrades during three-phase fault and line-to-line faults. Additionally, total active power from PV systems is used to charge the ESS during three-phase fault and line-to-line fault.

V. DISCUSSIONS

The discrete hybrid PV plant without upgrades could not provide continuity of operation during balanced and unbalanced transmission line faults for the same operating conditions and ac grid conditions as in the MARS system when connecting to a low SCR and low inertia grid. The main reason for such behavior is insufficient short circuit strength in the ac grid that led to unstable operation of the discrete hybrid PV plant. To ensure enhanced stability, additional reinforcements such as synchronous condensers, shunt capacitors, and dampers were installed in the system. The synchronous condensers improved the short circuit strength of the system and enhanced the stability of the connected plant. Shunt capacitors and dampers were also installed in the system to reduce the harmonics produced by the PV and ESS plant inverters. A detailed comparison of the performance of discrete hybrid PV plants with the MARS plant at different locations with different fault magnitudes during balanced and unbalanced transmission line faults is performed.

From the analysis of the case studies in this research endeavor, it is identified that the discrete hybrid PV plant needs additional upgrades such as installation of SCs, shunt capacitors, and re-sized dampers to provide continuity of operation when connected to low SCR ac grids. It is also identified that with the controller upgrades, the SC requirement might be reduced that might prove to be an economical option in some credible scenarios. For the balanced faults, the hybrid PV plant with additional upgrades could provide stable Q_{poi} support in the scenarios where the fault location was at a long distance (600 km) and medium distance (300 km). In the case of nearby balanced faults, the stable transient performance of the hybrid PV plant is not guaranteed either with (or without) control upgrades or the higher SC ratings (3.5x the plant ratings). Further analysis is required for the scenarios where the fault location is closer to the plant (60 km) as initial studies have indicated unstable operation without additional control and/or hardware like SCs reinforcement. For the unbalanced faults, the hybrid PV plant could provide stable Q_{poi} in all of the scenarios. For the same scenarios (including nearby faults) and similar use cases such as balanced and unbalanced faults, the MARS plant provides stable transient performance and provides continuity of operation even when connected to low SCR ac grids without any additional reinforcements. From this fault analysis, it is observed that the MARS power plants could provide stable Q_{poi} in all of the scenarios irrespective of the fault location and fault magnitude.

VI. CONCLUSION

In this paper, a set of solutions that enable PE-interfaced resources to connect to low SCR and low inertia grids to operate without momentary cessation is presented. The solutions include: (a) addition of traditional upgrades such as SCs, shunt capacitors, and dampers to state-of-the-art hybrid PV plants so that they can provide voltage support (ensuring continuity of operation during balanced and unbalanced transmission line faults); and, (b) integrated PV-ESS plants that connect to HVdc and high-voltage ac transmission grids (MARS). The proposed solutions were evaluated under different operating conditions and fault types using EMT models developed in PSCAD enviroment. In addition to evaluating different solutions, a technical comparison is provided between the MARS system and the discrete hybrid PV plants. The MARS system provides continuity of operation without any additional ac upgrades. Costs associated with discrete hybrid PV plant when compared to MARS may be significantly higher with the introduction of upgrades needed in the hybrid PV plant.

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