

Comparison of Steady State Performances of Practical Large-scale PV Configurations

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Abstract—The concern regarding global warming and the advancement of power electronic devices have enabled the development of large-scale PVs (e.g. MW and GW range) in power systems. A number of internal layouts of AC collector grids are reported in the literature for the large-scale PV (LSPV). This study comprehensively assesses the static performance of various configurations of large-scale PVs. The PV systems are modeled in DiGSILENT Power Factory in detail. The widely used PV system configurations such as radial, star, ring, multi-ring, and multi-star have been considered in this study. From the results given in this paper, it is apparent that the PV system configuration has significant effects on fault current and active power injection. From the given results, it is evident that the control methods employed in PV systems also influence the steady state performance of the system.

Index Terms—Configurations, collector grid, equivalent model, large-scale PV, short-circuit current contribution.

I. INTRODUCTION

REQUIREMENTS for clean and safe energy solutions to meet the future electricity demand has prompted the integration of renewable energy. In early 2000, International Renewable Energy Agency (IRENA) identified solar PV (simply known as PV) as one of the promising technologies among all renewables. The PV market has significantly grown over the last decade. It is reported that the PV market added over 100 GW of capacity in the first half of 2018 with 6% annual growth [1]. Moreover, with the advancement of the power electronic devices, the size of PV systems has grown from a few hundreds of kW to hundreds of MW. Even a GW scale PV has already been commissioned in China [1], [2].

PV system growth is expected to continue with the advancement of power electronic devices and the decremental costs of the solar cell, inverters, and associated controls. However, the power systems have undergone some changes in the fundamental characteristics due to the distinct dynamic behavior of renewable based generation such as PV. The zero inertia and

the constraints in reactive power operations of large-scale PV (LSPV) have the potential to threaten the stability and security of the power systems [2], [3]. Moreover, the LSPV project costs millions of dollars in the initial investments. Therefore, these projects should be configured and operated effectively from a technical and economic point of view. Several studies have been conducted to examine the impact of PV power plants on stability, quality, and reliability of the host AC grid [3]–[8]. However, the LSPV system was represented by an equivalent model (i.e. single generator equivalent model) in most of these studies. This simplified model neglects the influence of the internal configuration on the overall capability of the PV system. Therefore, the detailed and improved model of the PV system is vital to explore the performance of such a system under numerous severe operating conditions. One of the main parts of the LSPV system is the collector grid. Different arrangements can be employed to form the PV configuration. Numerous configurations are commonly used in the LSPV power plant such as radial, ring, and star [2]. However, work has yet to be done to explore the influence of those configurations under different operating conditions on power system static and dynamic performance.

Several research efforts have been undertaken to investigate the capability of the PV system in providing ancillary service [3]–[7]. However, the capability as well as the fault current contribution of the individual units of the PV system are not explicitly considered. Cabrera et.al in [4], [5], [8]–[10] demonstrate the influence of the DC link and ambient conditions on defining the capability curve of a PV inverter based on the maximum and minimum active and reactive power under each operating condition. However, the PV inverter operational zones were not identical. Nevertheless, additional control limitations imposed on the PV system may reduce the overall system capability. Research in [11] and [12] reviewed the LSPV layout in terms of electric components, wiring, and PV mounting characteristics. The work in [13] has analyzed the advantages and disadvantages of various PV configurations based on central inverter topologies. The influence of line reactance (X) has been reported in [14]. It is apparent from [14] that the line reactance (X) has an influence in defining the limitations of the capability curve. In [14], the line reactance (X) was represented by summing up the inductances of the inverter filter and transformer (L_f), and the grid inductance (L_g). Hence, the collector grid reactance is not explicitly included. Moreover, the collector grid is usually made up of medium voltage cables. Therefore, the impact of

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the charging current needs to be considered in defining the capability of the PV system. Additionally, the medium voltage (MV) network has a high X/R ratio which results in high reactive power losses and low system strength.

System strength becomes a critical issue today in power systems with massive inverter-based generators. Those inverters have limited fault current injection and different dynamic characteristics for the fault ride-through capability. Moreover, the inverter system has relatively poor disturbance-rejection capability which could make PV system more vulnerable in a weak network. Significant research efforts have been made to examine the contribution of PV systems under fault conditions. The authors of [15] analyzed the fault current contribution from PV inverters for the faults within the collector grid in PV systems. The outcomes of this work are significant for designing the line protection system of the PV power plant. However, only the multi-radial configuration is used in [15]. Nevertheless, the impact of the internal arrangement of other configurations on the fault characteristics should be included and investigated. Moreover, the system was divided into two parts (i.e. the downstream and upstream) during the faults. However, the contribution of each individual unit, and the impact of the internal configuration were neglected in [15].

Despite the extensive work on PV system layout, there is a lack of information about the internal topologies and their impact on the steady-state and dynamic performance of the system. This paper aims to fill those gaps in literature by comprehensively analyzing the impact of various PV system configurations on steady-state performance. The rest of the paper is arranged as follows: Section II demonstrates an overview of the PV power plant configurations. The methods used in this study for performance evaluation are presented in Section III. Section IV illustrates the comparative simulation results for various configurations. This paper concludes with a discussion on the results in Section V.

II. OVERVIEW OF PV POWER PLANT CONFIGURATION

This section briefly describes the various configurations available for the large-scale PV system.

A. Large-scale PV System

The main parts of a LSPV power plant are depicted in Fig. 1. The LSPV include PV modules, DC/AC inverters, MV transformers, MV feeders, HV transformer, and the transmission

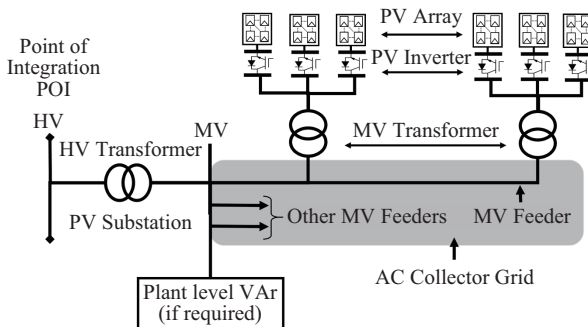


Fig. 1. Large-scale PV system layout.

line (known as the AC collector grid). The large-scale PV system may include an energy storage system and reactive power support systems based on the grid strength and the grid code requirements at the point of integration (POI). Utility-scale PV power plants are new to the energy sectors and yet are considered to be mature like wind power systems. Therefore, a few configurations and topologies for large-scale PV are reported in literature [16]. Nonetheless, the radial, ring, and star configurations are the most commonly used configurations for LSPV power plants [2], [17].

B. Large-scale PV System Configuration

There are tens to a few hundreds of PV inverters in the LSPV system which are distributed over an immense area (roughly 8,000–42,000 m²/MW see [1] and references therein). The MV transformer is usually connected very close to the PV inverter. Therefore, several feeders are used to collect the power from the MV transformers to the main substation. The number of feeders in a PV system depend on the configuration of the PV plant. The collector system can be based on underground cables, overhead lines, or a combination of both. In the radial configuration, the AC output of the PV inverters is stepped up through the LV/MV transformer. Then several feeders are connected in series through medium voltage feeders as shown in Fig. 2. The busbar is protected with circuit breakers on both sides. However, if there is a fault on the busbar, all of the downstream feeders will be isolated. Therefore, the radial configuration has low reliability compared to other configurations. The multi-radial collector is a modified version of the radial configuration with improved reliability.

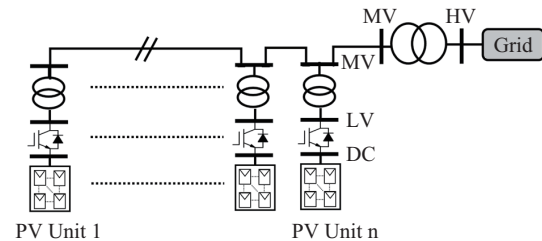


Fig. 2. Radial configuration.

Ring configuration, as depicted in Fig. 3, is employed to overcome the reliability issue of radial configuration by providing another path for the PV current during the internal fault in the system. This feature is associated with an additional cost of upgrading the cable's capacity to meet $N - 1$ contingencies. Accordingly, it should be taken into consideration that the maximum current which may pass through each feeder is designed to minimize the undelivered power under fault. Nevertheless, multi-ring collector configurations can offer a trade-off between reliability and cost. Each ring in this configuration can be formed based on its electrical output or geographical characteristics [8].

Star configuration as given in Fig. 4 has the best reliability since each single PV generator unit is directly connected to the medium voltage substation (primary). The connection in star topology eliminates the reliability issue due to the failure

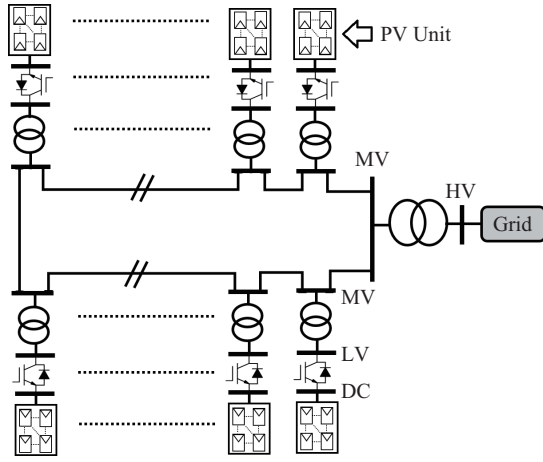


Fig. 3. Ring configuration.

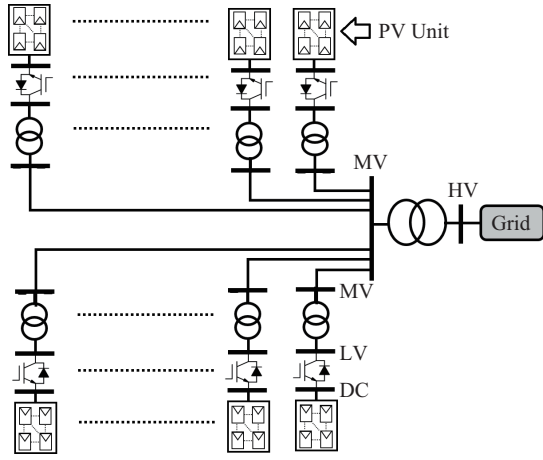


Fig. 4. Star configuration.

of other components. In the star configuration, the high cost has resulted from the cable cost for long feeders. However, this cost can be reduced by using the multi-star configuration where a group of the PV generator units will be gathered to a bus bar, and then one feeder could carry the current to the main MV bus [2]. Nevertheless, the multi-star has low reliability.

A further investigation is required to identify the power losses in each configuration to give better guidance to the LSPV planners and operators. For all those configurations, the collector grid is assumed to be an AC MV network. The research work in [18] was devoted to propose an MV DC collector grid which may lead to a better quality of output power. However, Li *et al.* [19] carried out a detailed cost comparison analysis of AC and DC collector systems for large-scale PV power plants. The DC collector would cost 30% more than the AC collector as reported in [19]. Moreover, the authors highlighted other challenges associated with the DC collector system such as an absence of protection devices and standards. The DC devices available in the market, such as circuit breakers, are yet to achieve the required voltage level for such applications. Nevertheless, the authors overlooked the DC light technology developed by ABB [20] or the Medium Voltage Direct Current Power Link Universal System (MVDC

PLUS) developed by Siemens [21]. The application of such collector grid topology could be more efficient than the AC collector system from an economic and technical viewpoint. However, based on the current industrial practices, the AC collector grids are only considered here for this analysis.

III. METHODOLOGY

In this research, several cases have been formulated to investigate the impact of the collector grid configurations and the control methods on the steady-state performance of the LSPV system. The simulation was carried out using DigSILENT Power Factory Ver. 2019 [22]. Each case study represents a 100 MW PV power plant with specific collector grids and control schemes. The 100 MW PV system is made up from 10 PV units each with a 10 MW rating. In all case studies, the same number and rating of PV units have been used. Four 2.5 MVA 0.4/20 kV transformers are used in parallel for each PV unit. Each feeder length was considered to be equal to 1 km. In all configurations, the PV power will be gathered at the main MV bus. At the PV substation, the power is delivered through the high voltage (HV) transmission line and connected to the infinite bus test system. All the PV system configurations are evaluated against different control methods i.e. unity power factor mode, 0.95 power factor, and voltage control method. The transformer and the HV line resistance and reactance are selected as shown in Tables I and II.

TABLE I
MV AND HV TRANSFORMER PARAMETERS [19]

MVA	HV Side	LV Side	Pos. Sequence Impedance	
			X (p.u)	R (p.u)
110	400	20	0.16	0.002
2.5	20	0.4	0.07959	0.008

MV = medium voltage; HV = High voltage

TABLE II
HV LINE PARAMETERS [19]

Voltage (kV)	Length (km)	Pos. Sequence Impedance	
		X (Ω/km)	R (Ω/km)
400	100	0.34	0.033

The aim of these analyses is to compare the prior mentioned configurations in terms of power flow as well as their short circuit contribution. Accordingly, the main parameters influencing the steady-state performance of the feeders are impedance and shunt capacitance. An equivalent model of each configuration, as shown in Fig. 5, has been developed in this paper using the method proposed by NREL [23]. All n number

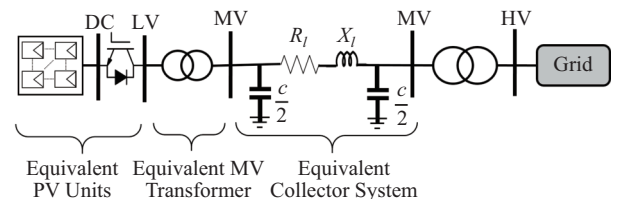


Fig. 5. Large-scale PV equivalent model.

of PV units are converted into a single equivalent machine as per the method given in [23]. The equivalency of cables and transformers (i.e. n number of cables and transformers to single cable and transformer) has been considered. The equivalent model has been tested against the detailed model to determine the accuracy for the steady-state performance assessment.

A. Steady-state Performance

Power system steady-state performance is an important issue that needs to be taken into account in the planning and operational stages. With high penetration of PV, it is vital to investigate the influence of different designs and internal configurations of the PV system and the operational schemes on system efficacy, capability, and reliability of service. Active and reactive power flow as well as the short circuit contribution can be used as the main indices to compare various configurations of LSPV.

It has been reported that the harnessing maximum power from the PV system is affected by the energy losses in the AC collector system due to prolonged and lengthy cables. Therefore, the identification of the right configuration is essential for the PV system planners to maximize the benefit from the PV system. Moreover, the reactive power provision is vital as the PV system is required to provide local voltage regulation and support [24]. It has been reported that often the PV systems are equipped with reactive power compensation devices such as STATCOM, SVC, and capacitor banks to offset the reactive power losses in the collector system [24]. Therefore, the identification of the collector system with minimum VAR support is sought. For this analysis, unity power factor, 0.95 power factor, and voltage control mode are considered.

High penetration of inverter-based generators will affect the system strength as reported in [25]. Hence, LSPV power plants are required to contribute to the fault current during the short-circuit. Fault current will be injected from all PV inverters which are distributed over the vast area. However, the fault current contribution from the LSPV system may be affected due to the various configurations and control schemes. Therefore, the PV system short circuit contribution needs to be assessed for different configurations and control methods.

B. Equivalent Collector System

In the LSPV system, the collector systems are made up of several feeders with different values of impedance and shunt capacitance based on the current capacity as given in Fig. 6. Based on the collector system configuration, these feeders relate to each other and finally, the main MV substation is connected either in series or parallel. The collector system equivalence method developed in [23] can be used to find the equivalent representation for each topology. Equation (1) can be used for the series connection such as radial configuration while (2) could be used for the parallel cables connection such as star configuration.

For other configurations where the cables are connected in series and parallel as presented in Fig. 7, equation (3) can be employed to find the equivalent feeder impedance (Z_T). The equivalent shunt capacitance of the feeders (C_T) can be

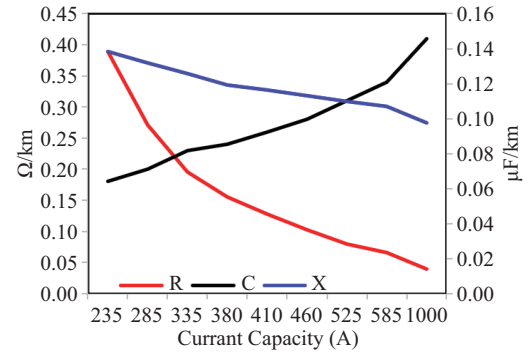


Fig. 6. Medium voltage (MV) feeder characteristics [22].

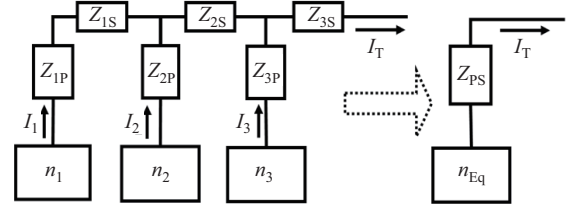


Fig. 7. Equivalent of series and parallel MV feeders.

found by summing all the capacitance (C_i) within the collector grid by (4) assuming that the unity voltage is across the cables under normal conditions. The equivalent impedance of the MV voltage transformers (Z_{TR-T}) can be found by dividing the impedance of a single transformer (Z_{TR-i}) by the total number of the MV transformers n as in (5) [23].

$$Z_S = \frac{\sum_{m=1}^n m^2 Z_m}{n^2} \quad (1)$$

$$Z_P = \frac{\sum_{m=1}^n n_m^2 Z_m}{\sum_{m=1}^n n_m} \quad (2)$$

$$Z_T = \frac{\sum_{i=1}^{np} n_i^2 Z_{iP} + \sum_{i=1}^{ns} (\sum_{j=1}^{ns} n_j)^2 Z_{iS}}{(\sum_{i=1}^{np} n_i)^2} \quad (3)$$

$$C_T = \sum_{i=1}^n C_i \quad (4)$$

$$Z_{TR-T} = \frac{\sum_{i=1}^n Z_{TR-i}}{n} \quad (5)$$

where Z_S and Z_P are the equivalent impedance of the series and parallel feeders. The equivalent impedance of the individual series or parallel groups is represented by Z_m . The number of PV inverters in each series or parallel string are designated by n , and m is the index.

C. Configuration Competency

The configuration competency is determined based on the feeder active and reactive power flow [18]. In each feeder, there would be active power losses (P_{line}) due to the line resistance (R_L) and these losses are related to the square of the current (I) as in (6). The reactive power (Q_{line}) is consumed by the line reactance (X_L) and related to the square of the current as in (7). However, the shunt capacitance (C) may inject charging current (I_c) as in (8) that may generate some reactive power (Q_c) with respect to the square of the line V

and system frequency (f) as in (9).

$$P_{\text{line}} = I^2 R_L \quad (6)$$

$$Q_{\text{line}} = I^2 X_L \quad (7)$$

$$I_c = 2\pi f C(V/\sqrt{3}) \quad (8)$$

$$|Q_c| = 2\pi f C V^2 \quad (9)$$

D. Short-circuit Current Contribution

The short circuit current contributions (SCCCs) of each configuration are estimated for the worst case, i.e. three-phase solid fault at the MV substation. The focus of this analysis is to evaluate the studied configurations in terms of their fault current contributions. The PV inverter can supply the fault current up to 1.2 p.u. of the rated current [26]. In this study, the rated fault current and double the rated fault current are considered. The SCCC is compared for those configurations under different control methods. The impact of the configuration can be seen in the total fault current injection due to the same rating of all inverters. Therefore, for each configuration, the contribution can be found as a percentage of the rated fault current capacity as in (10). Furthermore, the influence of these configurations and the sensitivity of the total fault current under enhanced fault current capability has been assessed based on (10) and (11).

$$\text{SCCC}\% = \frac{\text{PV_SCC}_T}{\sum_1^n \text{PV_SCC}_{Ri}} \quad (10)$$

$$\text{SCCC}\%_0 = \text{SCCC}\%_{\text{R}} - \text{SCCC}\%_{\text{NR}} \quad (11)$$

In (10) and (11), PV_SCC_T is the total SCC injected from LSPV to the grid, PV_SCC_R is the rated SCC of each PV inverter, $\text{SCCC}\%_{\text{R}}$ is the SCCC% at normal rating, and $\text{SCCC}\%_{\text{NR}}$: SCCC% at a new rating. Fig. 8 shows the influence of the AC collector grid on the inverter PQ capability. From this figure, it is evident that the line reactance X in the collector grid would limit the PQ capability. Therefore, it is obvious that the AC collector system with various configurations would have different levels of fault current contribution from the PV system.

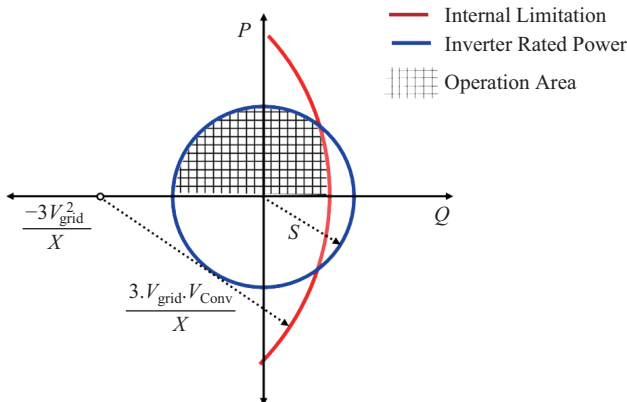


Fig. 8. PQ capability of PV inverter in a LSPV power plant [8].

IV. RESULTS AND DISCUSSIONS

Several case studies have been carried out to examine the impact of various configurations on the steady-state performance of the LSPV system. The main configurations such as radial, ring, and star are considered in this section. However, for the LSPV system it is not practical to have the whole system built in one configuration. Hence, the idea of multi-radial, multi-ring, and multi-star are also included in this study for the analysis.

A. Current Injection

The influence of LSPV system collector grid topologies and the control methods on the total delivered current from the PV is depicted in Fig. 9. Generally, the configuration has a limited influence on the injected current. However, the control method would strongly affect the total current delivered to the grid. With the power factor control method, more current will be injected to the grid. On the other hand, operating PV inverters at a 0.95 power factor result in a considerable reduction in the amount of the current supplied from the PV power plant to the grid.

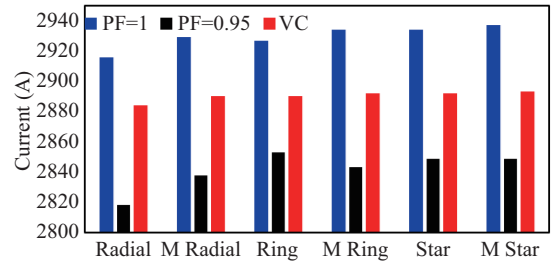


Fig. 9. Variations in PV system current.

B. Active Power Losses

Table III shows the active power losses affected by the collector grid as a percentage from the rated MW power of the PV plant. The active power losses account for both the losses at the feeder and the MV transformer. The active power losses in the feeder are a reflection of the square of the injected current as in Fig. 9 multiplied by the line resistance. As observed, the control methods have a minor influence on the active power losses. Nevertheless, the LSPV configuration affects the active power losses, thereby, influencing the efficiency of the system. For instance, the radial configuration with the highest equivalent resistance results in more active power losses. On the other hand, the star configuration with

TABLE III
ACTIVE POWER LOSSES

Configuration	PF = 1	PF = 0.95	VC
Radial	2.31%	2.40%	2.30%
Multi-Radial	2.59%	1.70%	1.60%
Ring	1.18%	1.30%	1.10%
Multi-Ring	1.04%	1.20%	1.00%
Star	1.22%	1.40%	1.20%
Multi-Star	1.18%	1.30%	1.10%

PF = Power factor; VC = Voltage control.

low equivalent resistances is about 1.20% more efficient than the radial configuration.

C. Reactive Power Performance

The reactive power performance of the LSPV power plant is an important issue which could affect the voltage regulation at POI. It is apparent that both control methods and the system configuration play a role in defining the total reactive power pattern in the LSPV system (supply to or absorb from the grid) as given in Fig. 10. With the unity power factor or voltage control methods, the PV system needs reactive power from the grid or plant level VAR devices such as capacitor bank, SVC or STATCOM. It should be noted that almost the same amount of VAR is supplied to the grid by all LSPV configurations. However, the amount of VAR required by the PV system varies with the configurations for the voltage control method. The radial collector system requires more VAR support from the host AC grid. It should be noted that in the radial collector, the PV inverters are divided into two parts: the upstream group and downstream group. The upstream supplied the reactive power while the downstream absorbed the reactive power to achieve the voltage control setpoint. To overcome this issue, a higher voltage control setpoint can be made at the downstream converters. In the voltage control method, the inverter voltage is locally controlled by controlling the inverter low voltage terminal. Nevertheless, central control can be used where a substation MV or HV bus needs to be chosen as a controlled bus with specific set voltage. However, an external station control method needs extra communication lines between the MV substation and the PV inverters. Therefore, the delay of communication signals should be taken into account. Table IV demonstrates the voltage at the POI. Similar to their influences on the reactive power, the configurations have limited impacts on the POI voltages. However, control methods will strongly affect the voltage profile at the POI. As shown in Table V, the 0.95 power factor method results in more VAR, and it is believed that the POI voltage will be the highest when compared with other control methods.

TABLE IV
VOLTAGE IN MV BUS

Configuration	PF = 1	PF = 0.95	VC
Radial	0.972	1.03	0.98
Multi-Radial	0.974	1.031	0.984
Ring	0.977	1.034	0.987
Multi-Ring	0.976	1.031	0.988
Star	0.975	1.032	0.987
Multi-Star	0.975	1.031	0.987

PF = Power factor; VC = Voltage control

TABLE V
SHORT-CIRCUIT CURRENT CONTRIBUTION

Configuration	PF = 1	PF = 0.95	VC
Radial	88.71%	92.14%	89.10%
Multi-Radial	90.05%	93.02%	90.54%
Ring	90.61%	93.41%	91.14%
Multi-Ring	90.85%	93.09%	91.42%
Star	91.12%	93.76%	91.68%
Multi-Star	90.88%	93.58%	91.49%

PF = Power factor; VC = Voltage control

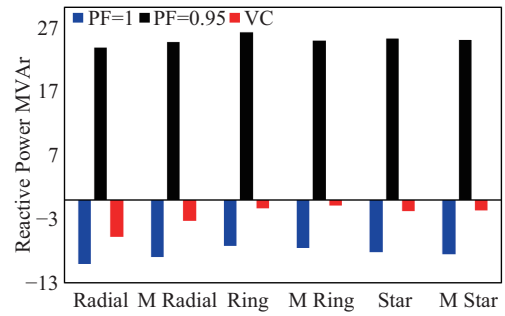


Fig. 10. Reactive power performance of various configurations.

D. Short-circuit Current Contribution

In general, the PV system has the capability to contribute to the fault current. PV configurations and control methods may influence the SCC contribution, as shown in Table V. The radial collector has the lowest SCCC while the ring and star collector have nearly similar SCCCs. The impact of collector topologies and the control methods are also examined. As illustrated in Fig. 11, in general, the controls in the PV have a slight impact on SCCC. However, the configurations play a major role in defining the total SCCC under the extended ability of PV to inject fault current. In the radial configuration, the total fault current contribution percentage will be reduced by almost 10% for the double SCC rating of PV inverters. This would be further reduced to 8% for star and ring configurations.

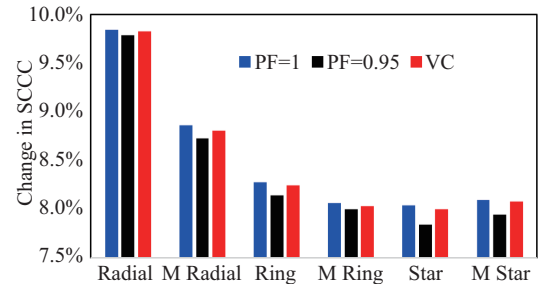


Fig. 11. Change in short-circuit current contribution under different contributions.

Another issue that needs further investigation is the fault current distribution among the PV inverters. Fig. 12 shows the distribution of the fault current in PV units. In the radial configuration, the PV inverters inject different current during the fault, primarily affected by the electrical distance from the fault location. Thus, the inverters located close to the fault inject more current while the inverters located at the end of the grid supply less current. The distribution can be improved for the multi-radial system as the electrical distance to the fault is reduced in this configuration. In the star configuration, the same amount of fault currents is distributed among inverters since the inverters are in the same distance from the fault.

E. Equivalent Model

As mentioned in Section III, the main purpose of the investigation is to examine the steady-state performance of

each configuration under different control schemes (primarily the reactive power control). The main difference among the various configurations of LSPV is due to the feeder parameters. Therefore, the equivalent representation of the collector system is obtained for each configuration for comparison as shown in Table VI.

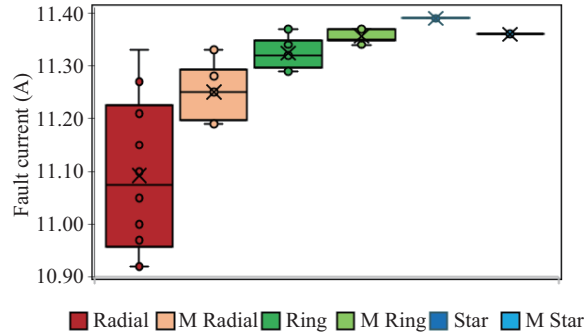


Fig. 12. Fault current distribution of PV unit of different contribution.

TABLE VI
COLLECTOR GRID EQUIVALENT PARAMETERS

Configuration	R_{eq} (Ω/km)	X_{eq} (Ω/km)	C_{eq} ($\mu F/km$)
Radial	0.049	0.122	10.100
Multi-Radial	0.028	0.065	6.260
Ring	0.013	0.032	14.760
Multi-Ring	0.008	0.020	9.840
Star	0.016	0.015	2.600
Multi-Star	0.014	0.021	2.120

Those configurations have different values of equivalent impedance and shunt capacitance. Hence, it is expected that they may exhibit different steady-state performances. Moreover, it is worth noting that the equivalent parameters are reduced, when the system is divided into two identical sub-systems. The radial configuration has the highest equivalent impedance value (Ω/km). The ring has the lowest equivalent resistance while the star has the lowest equivalent line reactance. The shunt capacitance is also varied among those configurations with the highest value in the ring collector. On the other hand, the star configuration has the lowest shunt capacitance value.

The accuracy of the equivalent model of the LSPV system with equivalent representations of collector grids has been tested against the detailed model. Those analyses are also carried out under different operating conditions of the PV. Fig. 13 displays the changes in the PV total current when

the equivalent model is used as compared to the detailed model. The equivalent and detailed models exhibit a similar current in the ring and star configurations under the voltage control mode. The injected current from the equivalent and detailed models is different when a power factor control is implemented in the PV system. However, it is worth noting that the percentage of change is less than 0.15% for the worst case scenario.

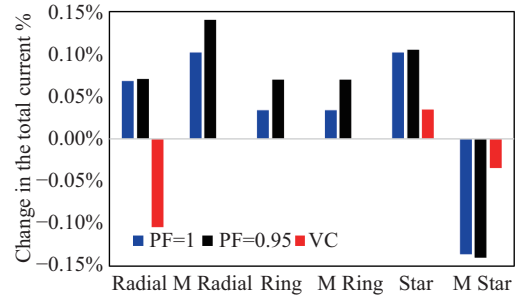


Fig. 13. Change in total current for various PV configurations.

F. Summary

The optimal configuration can be selected based on cost and performance indices. Table VII summarizes the collector configurations in terms of their cost and technical characteristics. The major cost is associated with MV cables since different cables with current ratings have been used in these LSPV configurations. The construction work related to the underground feeder also contributes to the configuration cost. However, the cost associated with the cables has been considered for simplicity.

The reliability is another issue that needs to be taken into account. The failures of MV feeders and transformers and their consequences are considered for the reliability assessment. The radial feeder has the lowest reliability as the failure of the feeder close to the PV substation results in losing all PV units in the LSPV. The ring and star configurations have better reliability, as the failure of any feeder may have minimal effect on overall PV delivery.

Simulation results indicate the PV configuration effects on the steady-state performance of the system. It is also noticed that the system performance may be improved while the configuration is divided into more parts. The radial configuration has a more prominent line impedance which results in the lowest performance index for those configurations under all

TABLE VII
COLLECTOR GRID CONFIGURATION CHARACTERISTICS

Configuration	Cost	Reliability	Steady State Performance								
			Active Power Losses			Main MV bus voltage			Fault Current Contribution		
			PF = 1	PF = 0.95	VC	PF = 1	PF = 0.95	VC	PF = 1	PF = 0.95	VC
Radial	4	6	5	6	6	6	1	6	6	6	6
Multi-Radial	3	5	6	5	5	5	2	5	5	5	5
Ring	6	1	2	1	2	1	6	2	4	3	4
Multi-Ring	5	1	1	1	1	2	2	1	3	4	3
Star	2	1	4	4	4	3	5	2	1	1	1
Multi-Star	1	4	2	1	2	3	2	2	2	2	2

Cost and performance index 1–6 where 1 is the best and 6 is the worst

control methods. On the other hand, the ring and star configurations perform better. The ring configuration is the best in terms of power flow competency while the star configuration shows better performance in terms of short circuit current contribution. Moreover, the ring configuration will cost more due to the upgraded cable capacity for reliable operation. The optimal configuration among the ring and star configurations can be determined by a comprehensive cost study that includes cable costs and energy costs. Table VIII summarizes the influence of configuration and control methods on the steady-state performance of the PV system.

TABLE VIII
SUMMARY OF PERFORMANCE

Performance	Effect	
	Control Method	Configuration
Current Injection	High	Medium
Active power	Medium	High
POI Voltage	High	Medium
Reactive power	High	Medium
Fault Current	High	High

V. CONCLUSIONS

In this paper, the influence of the LSPV configuration on steady-state performance has comprehensively been discussed. The AC collector grids, and system components have been modeled in this study considering the realistic LSPV implementation around the world. From the presented results, the following conclusions can be drawn:

- The collector grid topologies are critical for PV systems. However, the collector grid topologies have limited influence on steady-state performance compared to the control schemes.
- From the results, it is evident that the reactive power performance for the ring, multi-ring, star, and multi-star configurations have almost similar characteristics under the voltage control scheme. Moreover, the similar trends can be observed under a 0.95 power factor for all configurations.
- Both the collector grids and control schemes have a significant influence on the fault current contribution of the PV system. Significant changes in the fault current contribution and distribution of fault current under various operating conditions can be noticed in the radial configuration compared to other configurations. The changes in fault current and SCCC are small for start and multi-start configurations.
- In reality, the radial configuration of the LSPV is widely used due to the lower cable cost associated with the configuration. However, from the analysis results, it is apparent that the radial configuration encounters higher active power losses compared to other configurations. Moreover, the short-circuit contribution for the radial configuration is also low compared to the other configurations.
- The equivalent system model for various LSPV configurations has been presented in this study. From this work, it is evident that the equivalent collector grid parameters are different for different configurations. The higher resistive and reactance values can be noted for the radial configuration while the ring configuration exhibits higher equivalent shunt capacitance. It should also be noted that the variations in the

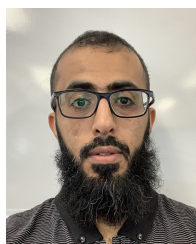
total current (i.e. active and reactive) of the configurations for the detailed and equivalent models are less than 0.15%.

This paper focuses on analyzing the implications of the LSPV configuration on the steady-state performance. A future study would investigate optimal collector grid configuration for dynamic performance assessment. In this paper, the individual scenarios are developed with the multi-radial, ring, and star configurations, and the implications of these configurations are assessed under different operations. The mixed configuration (i.e. two or more different configurations together) is yet to be used in practice. A future study would examine the performance of such a system and to what extent the LSPV can be divided into multi-configurations that will result in an optimal design from a reliability, technical, and a cost-effective point of view. Moreover, the interdependency of LSPV configurations and dynamic performance will be the significant subject of future research.

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