Impact of Grid Impedance Characteristics on the Design Consideration of Utility-Scale PV Systems

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***Abstract*—This paper proposes the key factors of the grid impedance characteristics and grid strength to achieve the maximum power transfer capability of the utility-scale PV systems. The short circuit ratio (SCR) and resistance to inductance ratio (R/X), along with grid voltage at the point of common coupling (PCC), directly impact power transfer capability. The study finds that a higher SCR and a lower R/X ratio improve power transfer capability. For resistive grids, increasing the voltage at PCC beyond the rated voltage is sufficient for maximum power transfer, while for inductive grids, the rated voltage is suitable for power transmission. To enhance the SCR and system stability, the study recommends incorporating a battery energy storage system (BESS). Additionally, adding transmission lines between buses significantly increases the SCR. The study's findings were verified through DIgSILENT Powerfactory simulations.**

***Keywords*—** *Grid impedance, short circuit ratio, battery energy storage system, maximum power transfer capability*

I. INTRODUCTION

Increasingly, power systems across the globe are incorporating inverter-based renewable generation due to advancements in technology that have lowered costs. The adoption of this technology is complemented by significant advancements in energy storage technology, which enables the integration of high levels of variable generation from renewable resources [1]

The research work conducted in [2] has focused on how the maximum power transfer capability is influenced by grid strength and impedance characteristics. The study found that the maximum power transfer capability can be increased by either increasing the short circuit ratio (SCR) or decreasing the resistance-inductance ratio (R/X) of the grid impedance. The research indicates that higher voltage at the point of connection can enhance transmission capability in resistive grid conditions. Low grid strength can result from increased penetration and greater separation between renewable energy sources and the primary power grid, leading to power limitation issues. To analyze the inverter power transfer maximum capacity, the researchers conducted various case studies involving resistive and inductive grid impedance with multiple grid strengths. The study concludes that power grids with higher SCR or lower R/X ratio have greater power transfer capacity. Moreover, the authors simulate the results according to the system design in Fig. 1 by MATLAB. It has been found that when SCR > 2 and R/X < 1 , the system stability is insured, which enhance the system robustness when the transmitted power is maximized.

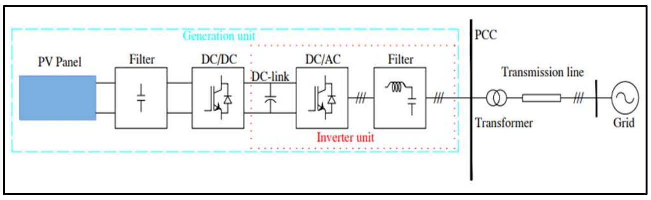

Fig. 1: Grid connected a Solar PV system.

The previous published papers are focused on how to improve the control system and working principles of grid-connected inverters to achieve the maximum power transfer [3-5]. The challenges of integrating high levels of renewable energy sources (RES) into the European transmission grid were discussed in [6-7]. The analysis demonstrates that high-RES penetration can lead to significant transmission network loading, resulting in congestion and the curtailment of renewable energy production. The studies stated that a combination of transmission network upgrades, demand response programs, and energy storage systems can help mitigate these challenges. Brown's research highlights the need for careful planning and management when integrating high levels of RES into the grid.

The authors in [8] provided a comprehensive overview of HVDC control strategies in weak AC grids. The study emphasizes the increasing importance of HVDC technology for long-distance power transmission, and discusses the various components of HVDC systems, including rectifiers, inverters, and DC cables. The authors highlighted the challenges associated with HVDC control in weak AC grids, and recommended the development of advanced control strategies and the use of modern control devices to improve the performance of HVDC systems. Overall, the paper emphasizes the importance of proper HVDC control to ensure the reliable and efficient operation of the power system.

The study in [9]. examines the limitations of Voltage Source Converter transmission systems caused by the strength and impedance of the AC system. The paper discusses the inability of VSC systems to provide fault current, its sensitivity to AC system impedance, and its limited ability to provide reactive power. The authors illustrated the impact of AC system strength and impedance on VSC transmission using a case study to emphasize the importance of proper planning and design for reliable and efficient operation of VSC transmission systems, particularly in weak AC networks. paper [10] investigates the impedance characterization of utility-scale renewable energy and storage systems using a multi-megawatt grid simulator. The study shows that impedance measurements can be used not only for the mitigation and assessment of dynamic stability issues but also as a means for high-fidelity verification and evaluating novel technologies, like grid-connected inverters. With the emergence of new interconnection standards for solar PV and wind turbines based on impedance response specs, multi-megawatt grid impedance measuring simulation systems, like the one presented in this study, will be important in the future.

Authors in [11] investigated the impact of grid impedance on the stability of a grid-connected PV generator. Through simulation, the researchers integrated the PV generator's control system with the inverter, which included multiple-loop control schemes for power, voltage, PLLs, and current loops. The study found that increasing the grid impedance can weaken high-frequency (>300 Hz) stability, and decrease low-frequency oscillation (60 Hz). By considering the interactions between various loops, the researchers developed a complete PV generator model with impedance analysis, used to examine high-frequency stability primarily controlled by the PLL and current loop. The study results distinguish the various ways in which grid impedance can affect the low- and high-frequency stability of PV generators. The outcomes of hardware-in-loop (HIL) tests confirmed the theoretical analysis. The main focus of paper [12] is to investigate the instability mechanism of a grid-connected PV station operating under weak grid conditions and subjected to fluctuations in solar radiation. The study utilizes a small-signal model of the PV inverter to obtain the impact on the output power of the solar panels, considering both the nonlinearity of PV cells and the solar radiation diversity. The researchers found that there is a nonlinear relationship between the output impedance of the PV inverter and the intensity of solar radiation. To confirm the proposed impedance model, the output impedance of the inverter was measured in different operating modes.

The single-phase PV inverters behavior connected to low voltage grids, to show the impact of harmonics on the grid strength was conducted in [13]. The study concluded that harmonic instabilities can occur due to the interaction of the control unit of the inverter, filters and the grid, and power grid. These instabilities are named as such because they arise from the inverter control's interaction with the power grid's impedance at harmonic frequencies, irrespective of the power active or reactive at the fundamental frequency. In power electronics, the impedance of the power grid is always assumed to be an RL-equivalent, allowing the Nyquist criteria to determine the critical RL-combination at which the inverter states unstable. However, resonances in the power grid impedance can cause the Nyquist criterion to be used incorrectly to determine stability. Recent field tests have shown that these resonances are mainly responsible for the harmonic instabilities observed in PV inverters. The examines a control strategy for distributed PV inverters based on real and reactive power control, to prevent overvoltage on the distribution network and increase renewable generation hosting capacity. The study in [14] discussed the challenges associated with the integration of distributed PV systems into the grid, including voltage regulation and power quality issues. The study also presented simulation results to demonstrate the effectiveness of the proposed control strategy. The authors suggested that the control strategy could be implemented in practical systems to facilitate the integration of distributed PV systems into the grid.

The researchers in paper [15] proposed an reactive power adaptive control strategy for PV power plants to enhance the power transfer stability and capability of ultra-weak grids. The paper highlighted the challenges associated with integrating PV power plants into the grid under ultra-weak grid conditions and presents simulation results to demonstrate the effectiveness of the proposed method. The author suggested that the adaptive reactive power control strategy can be applied in practical systems to improve the stability and the power transfer of PV power plants.

The strategy of injecting optimal value of reactive power, to address the challenges associated with integrating PV systems into the grid, is discussed in [16]. The study investigated the need for effective reactive power control to maintain grid stability and power quality. In addition, the study suggested adjusting the reactive power output of the inverter based on the voltage at the point of common coupling and the available reactive power capacity of the inverter. The paper presented simulation results to demonstrate the effectiveness of the proposed strategy in improving the voltage profile of the local grid and minimizing losses. The authors suggested that the proposed optimal local reactive power control strategy could be applied in practical systems to improve the stability and power quality of the grid.

II. SHORT CIRCUIT ANALYSIS

A. *Short Circuit Current*

The size and capacity of the power supply have a direct impact on the maximum value of the short-circuit current, which is a critical factor for the SCR. Compared to synchronous generators, inverters produce lower fault current with smaller amplitudes. However, the fault current from inverters lacks sufficient zero or negative sequence values to enable the directional relaying needed for identification and determining directionality. The lower levels of primary fault current can reduce sensitivity of the relay for fault or identify the polarization at certain bulk supply point sites. The lack of zero or negative sequence components can also result in incorrect polarized directional component declaration. In response, transmission stakeholders may update specific current relay settings when possible, and in other cases, the relays sometimes may need to be updated or replaced with more versatile technology.

1) Methodology

The IEC 60909 code provides a classification of short circuit currents and technical specifications depending on their amplitude (higher or lower) and the generator faults ranges distance. The direct current component of the fault current does not disappear but rather decays over time, and in real application, it only happens in the system for about 4-5 cycles at the fault instance. Therefore, the first step in determining the fault current of the DC component of, the asymmetrical fault current, and the network's short circuit peak current is to calculate the symmetrical fault current at the problematic site.

$$i_k = \frac{(c * U_n)}{(\sqrt{3} * Z_k)} \tag{1}$$

where, i_k is the symmetrical fault initial current, U_n is the voltage system (nominal) in kV, C is voltage factor and Z_k is the impedance of the short circuit at fault point. The Short circuit peak can also be illustrated as follows:

$$i_p = \sqrt{2} * k * i_k \qquad (2)$$

where, k is the ratio of R/X at fault point. Calculations are performed using DigSilent's IEC60909 short circuit calculation module.

- Initial symmetrical short circuit current (I''k)
- Steady-state short circuit current (I''k)
- Symmetric short circuit breaking current (Ib)
- Phase to earth initial symmetric short circuit current (LE - I''k)
- Phase to phase short circuit current (LL-I''k)
- Phase to phase to earth short circuit current (LLE-I''k).

Initial symmetrical short circuit current (Ik) and steady-state short circuit current (Ik) are important in ensuring that the equipment can withstand short circuit currents up to the nameplate values. Symmetric short circuit breaking current (Ib) is used to determine the circuit breaker's breaking capacity. These calculated short circuit currents are used for protection grading purposes.

2) *Modeling*

The DigSilent 2022 simulation software was used to model the 100 MW solar farm as a case study. The solar power plant is connected to a 110kV grid on the upstream side and at 0.4kV feeders on the downstream side. A fault was simulated on all buses, and it was observed that the grid side contributed the most to the short circuit current due to the grid's strength.

During the normal load flow study, the active and reactive power generation of the solar PV plant is controlled by the steady-state controller. However, in transient states, the inverter-dynamic model is used to control the active and reactive power generation. Table 1,2 and 3 provide the necessary information for the simulation stage.

Figures 2-3 demonstrates the behavior of the inverter and level of voltage when short circuit happens at point 2. Fault point 2 is considered to be 0.4 kV inverter main bus. Three-phase short circuit current is implemented on point 2. The behavior of the inverter is checked when the fault is happened. Figure 3 the electrical network which is used in this analysis shows multiple components between solar and bulk supply point. Tables 1-3 show the steady state values in case of the short circuit, grid parameters and impedance.

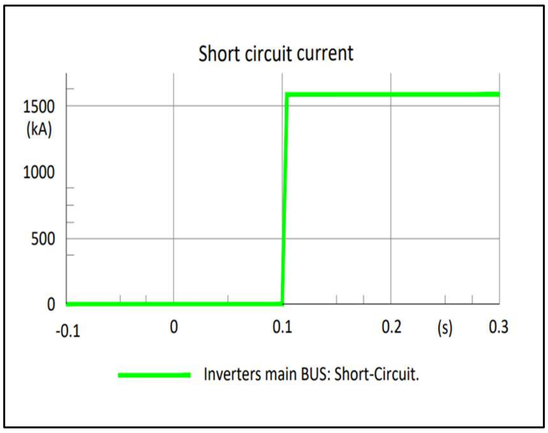

Fig. 2: Short circuit current occurrence.

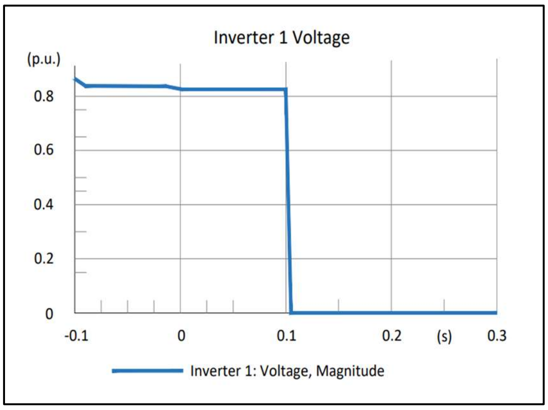

Fig. 3: Inverter 1 voltage in occurrence of short circuit.

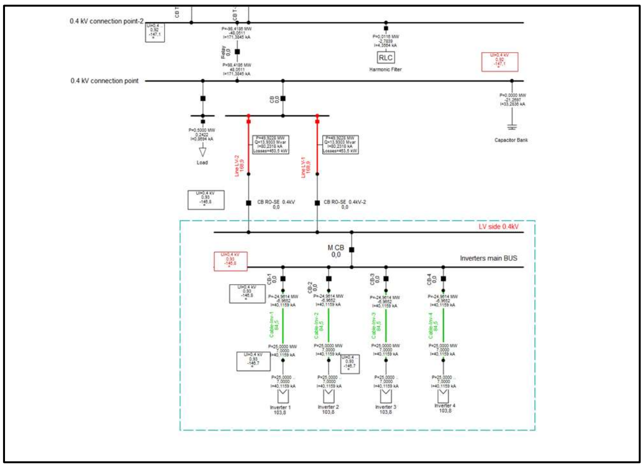

Fig. 4: Simulation network in digsilent powerfactory.

TABLE 1. STEADY STATE SHORT CIRCUIT CURRENT OF POINT 2 FAULT

Name	Ik"	Sk"	ip	Ib	Sb
	kA	MVA	kA	kA	MVA
Inverters main BUS	34	128	75	34	128

TABLE 2. PARAMETERS OF GRID-CONNECTED SYSTEMS.

V_g	Amplitude grid phase voltage	0.4kV
F_g	Grid frequency	60Hz
S_n	Rated power of Solar PV Plant	100MVA
$\mathbf{V_{DC}}$	DC voltage	1200V

TABLE 3. PARAMETERS OF GRID IMPEDANCE

	Grid phase voltage	0.4kV
Rg/Xg	R/X ratio of grid impedance	0.2
SCR	Short circuit ratio	10
X	Grid reactance	8.096
R	Grid resistance	1.619

B. *Short circuit ratio*

In electrical power systems, the short-circuit ratio (SCR) plays a crucial role in assessing the strength and reliability of a grid. By calculating the SCR, system operators can identify areas of the grid that may be susceptible to voltage instability, system perturbations, and potential protection system failures. This metric has traditionally been used to represent the voltage stiffness of a grid and is calculated at a resource's point of interconnection (POI). Low short-circuit ratios in certain areas of the grid may require additional monitoring or studies to mitigate any potential reliability issues. The generation resource mix transition has a significant impact on the transmission reliability, particularly as the grid incorporates more renewable energy sources. Voltage performance, frequency response, and system stability are critical considerations as the resource mix evolves. The SCR is an essential tool for system planners and operators to ensure that the power grid remains robust, reliable, and resilient in the face of changing energy demands and resource constraints.

The short-circuit ratio (SCR) plays a critical role in assessing the reliability and potential risks associated with the increased integration and penetration of inverters in the Bulk Electric System (BES). The conventional strength of a system, which is a measure of voltage stiffness, differs significantly from that of inverter-based technologies. By identifying areas of weakness in the grid using SCR at a specified point, such as a bus, it serves as a valuable screening tool. The SCR value varies for each bus within a system comprising multiple generators and transmission lines. Therefore, it is crucial to conduct a comprehensive evaluation of the SCR for each bus in the BES to ensure its reliable and efficient operation.

III. MATHEMATICAL MODEL

As the integration of inverter-based resources continues to replace synchronous resources, there is a critical point where the grid's strength may no longer be sufficient to support the stable operation of the power electronic converters connected to wind and photovoltaic generating resources. To identify weak grids in close proximity to power electronic converters, the short-circuit ratio (SCR) is utilized. Initially applied to identify weak grid conditions near high-voltage dc converters, this metric is now also being utilized for nonsynchronous plants. This metric is determined by a two-step process.

Firstly, a classical three-phase fault analysis is conducted at the interconnection/collector bus where the resource under study is connected to the grid. Secondly, the short-circuit capacity at the interconnection bus where the fault current source is situated is divided by the megawatt rating of the fault current source to calculate the SCR.

To determine the short-circuit ratio (SCR), various factors must be considered, such as the apparent power of the short-circuit at the (PCC), the total apparent inverter rated power, the amplitude of the grid voltage, and the rated voltage of the PCC and current amplitudes of the inverter. The rated voltage of the PCC is typically the same as the grid voltage, while the maximum current of the inverter, which is determined by the power semiconductor's ability to handle the current, is considered as the rated current of the inverter.

$$SCR = \frac{S_{scMVA}}{P_{RMW}} = \frac{V_g^2/Z_g}{V_{pcc} * I_{inv(rated)}} \tag{3}$$

where S_{scMVA} is the short-circuit apparent power at the PCC, P_{RMW} is the Inverter total apparent power, the amplitude of the grid voltage is V_g, I_{inv} and V_{pcc} are the inverter rated current and the rated PCC voltage amplitude; respectively. For the resistance of the grid the following formula is used:

$$Z_g = \sqrt{X_g + R_g} \tag{4}$$

$$\mathrm{P}_{inv(pu)} = \frac{P_{inv}}{S_N} = V_{pcc(pu)\times}\mathrm{I}_{d(pu)} = \tag{5}$$

$$\sqrt{\frac{V_{pcc(pu)^2} - 1}{2} + \frac{K_1}{4} + \left(1 - \frac{K_1}{2} + \sqrt{\frac{V_{pcc(pu)^2} + 1}{2} - \frac{K_1}{4}} \times K_2 \times \frac{R_g}{X_g}\right) \times \frac{1}{\frac{R_g 2}{X_g 2} + 1}}$$

$$\mathrm{P}_{grid(pu)} = \tag{6}$$

$$\sqrt{\frac{V_{pcc(pu)^2} - 1}{2} + \frac{K_1}{4} + \left(1 - \frac{K_1}{2} + \sqrt{\frac{V_{pcc(pu)^2} + 1}{2} - \frac{K_1}{4}} \times K_2 \times \frac{R_g}{X_g}\right) \times \frac{1}{\frac{R_g 2}{X_g 2} + 1}}$$

$$- \left[(1/SCR) \times \left(R_g/X_g\right)\right] / \sqrt{\left({R_g}^2/{X_g}^2\right) + 1} \tag{7}$$

$$K1 = SCR^2 . (V_{pcc(pu)^2} - 1)^2 + \frac{1}{SCR^2} \tag{8}$$

$$K2 = SCR . (V_{pcc(pu)^2} - 1) + \frac{1}{SCR} \tag{9}$$

Where X_g-reactance R_g-resistance of the grid K1&K2 are intermediate variables. The above formulas (4 &5) had been calculated with different R/X & Vpcc & SCR as the following:

TABLE 4. INVERTER & GRID POWER WITH DIFFERENT PARAMETERS

Grid Parameters		**Power (Grid) @Vpcc=1 p.u.**		**Power (Grid) @Vpcc=1.05 p.u.**		**Power &(Grid) @Vpcc=1.1 p.u.**	
R_g/X_g	**SCR**	**Pinv**	**Pgrid**	**Pinv**	**Pgrid**	**Pinv**	**Pgrid**
0.2	1	0.9473	0.7511	0.9844	0.7883	1.0195	0.8234
	4	0.9974	0.9484	1.0422	0.9931	1.0438	0.9948
	7	0.9921	0.9641	1.0236	0.9956	0.8917	0.8637
	9	0.9900	0.9682	0.9976	0.9758	0.6444	0.6226
	12	0.9879	0.9716	0.9322	0.9159	0.0000	0.0000
	15	0.9866	0.9735	0.8218	0.8087	0.0000	0.0000
	18	0.9856	0.9748	0.6243	0.6134	0.0000	0.0000
	21	0.9850	0.9756	0.0000	0.0000	0.0000	0.0000
	24	0.9845	0.9763	0.0000	0.0000	0.0000	0.0000
	29	0.9838	0.9771	0.0000	0.0000	0.0000	0.0000
1.5	7	0.6127	0.4939	0.8892	0.7704	1.0860	0.9671
	9	0.6001	0.5076	0.9370	0.8446	1.0860	0.9936
	15	0.5821	0.5267	1.0432	0.9878	0.0000	0.0000
	22	0.5735	0.5356	0.0000	0.0000	0.0000	0.0000
7	4	0.2641	0.0166	0.4677	0.2202	0.6747	0.4272
	9	0.1962	0.0862	0.6409	0.5309	1.0551	0.9451
	15	0.1743	0.1083	0.8899	0.8239	0.0000	0.0000
	18	0.1689	0.1139	1.0039	0.9489	0.0000	0.0000

According to equations (5) and (6), figures 6-7-8 represent the relation of the inverter power Pinv. (p.u.), the grid power Pgrid (p.u.) and the voltage of the PCC Vpcc (p.u.) with multiple SCRs and Rg/Xg ratios

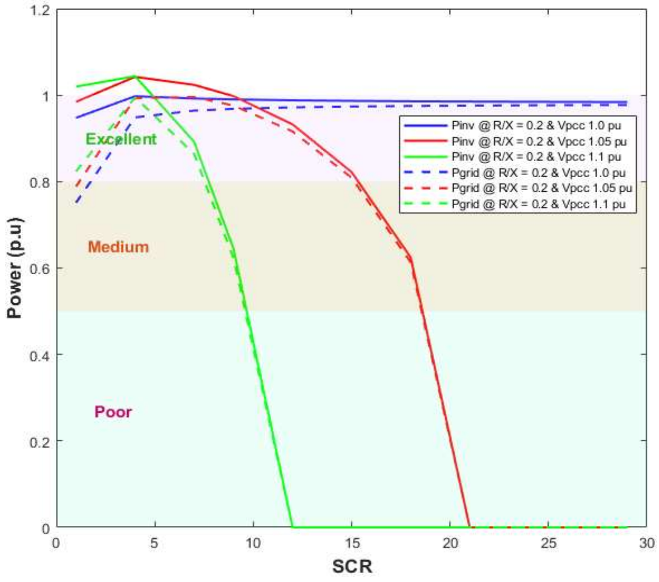

Fig. 5. Inductive grid with different SCR and voltage.

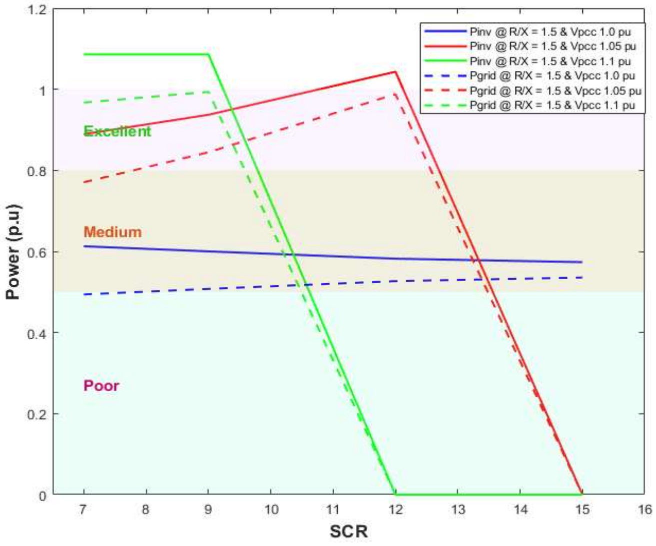

Fig.6. Resistive grid with different SCR and voltage

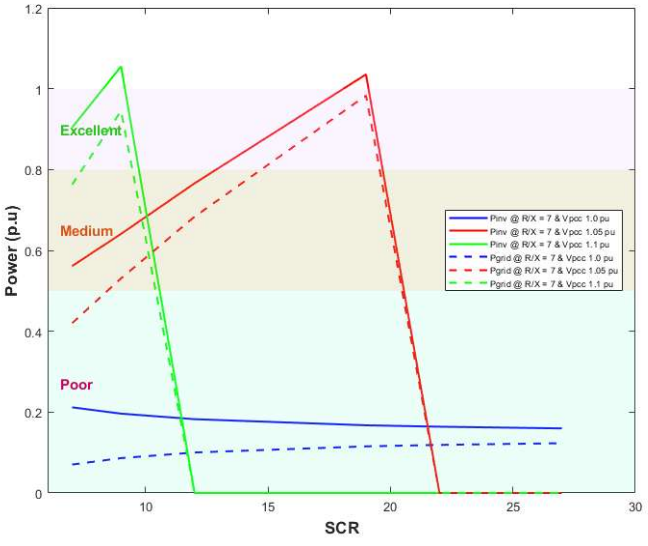

Fig.7. Resistive grid with different SCR and voltage

As shown in Fig. 5 (inductive grid with R/X = 0.2) multiple scenarios have been applied with different SCR and PCC voltages; it is revealed that in case of the inductive grid, the rated PCC voltage is appropriate for the power transmission. In Fig. 6&7 (resistive grid with R/X = 1.5 &7), also multiple scenarios were conducted, in the case of R/X = 1.5 and Vpcc = 1.05 p.u. the system start rising; however, the power transfer collapsed to zero after SCR = 12.3 while at Vpcc = 1 the power transfer stays in medium level. Moreover, in case of R/X = 7 the worst scenario is when the Vpcc = 1 p.u. since it always poor and for other voltages the SCR should be maintain at a certain point to keep the system stable.

IV. SIMULATION RESULTS

The simulation analysis is done using Digsilent powerfactory in order to verify the effectiveness of mathematical analysis. One exists electrical network is used to just analyze the power transfer changes once we increase and decrease the SCRs, R/X, PCC Voltages. The results are somehow close to the math analysis as the results always depend on the network parameters in real applications, which is not an ideal case. In addition to SCR and R/X ratio, the PCC voltage is a significant factor that impacts the power transfer maximum capacity of a system. As previously mentioned, inductive grids are best suited for power transmission with rated PCC voltage. On the other hand, resistive grids can benefit from a higher PCC voltage than the rated value for power transmission. The system capability is evaluated with different SCR, R/X, and Vpcc values. The maximum transfer capability of the Solar PV plant is evaluated in transient stability.

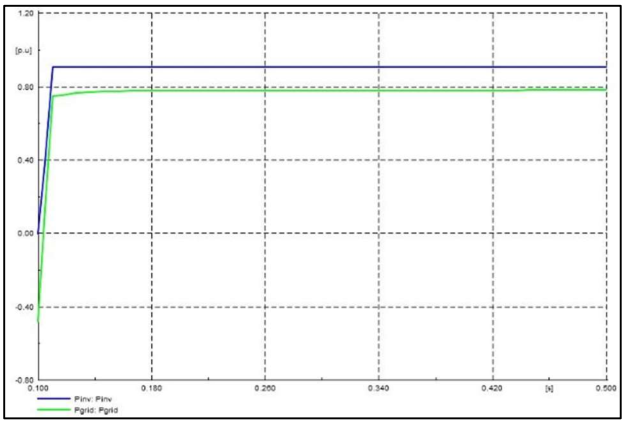

Fig. 8: Power Transfer (SCR=15, R/X=0.2 and V_{PCC}=1.05)

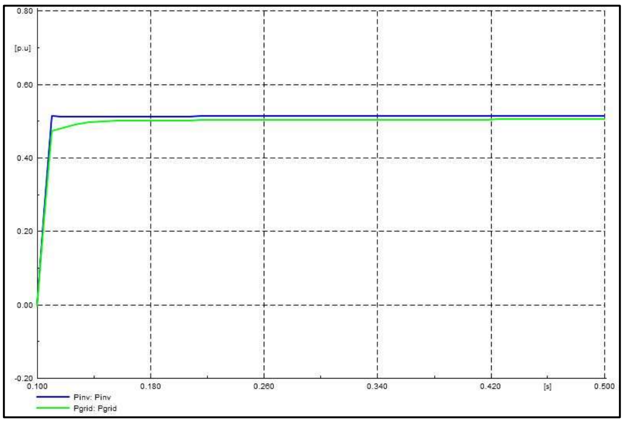

Fig. 9. Power Transfer (SCR=15, R/X=1.5, and V_{PCC}=1)

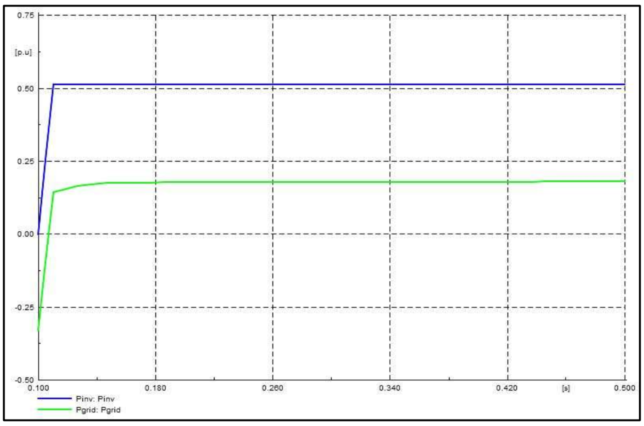

Fig. 10. Power Transfer (SCR=4, R/X=7 and V_{PCC}=1.05)

The maximum power transfer capability as shown in the simulations figures is different when we change some of the grid parameters. Furthermore, there is not a unique parameter for the real applications of the electrical networks to achieve the maximum power transfer. Each has a different scenario. Generally, Increasing SCR and decreasing R/X can enhance the power transfer maximum capability of the system as shown in the mathematical & simulation analysis. In addition, the short circuit power is important to increase the SCR. From the SCR formula which is equal to the short circuit power/Inverter rated capacity. Changing the SCR is required to change the short circuit power. Adding more transmission lines and battery energy storage system will increase the short circuit power as the below simulation results verified. The simulation results verify that adding more transmission lines and BESS enhanced the short circuit power which intimate to increase the SCR to acquire more power transfer. Table 5 summarize the SCR values with all scenarios.

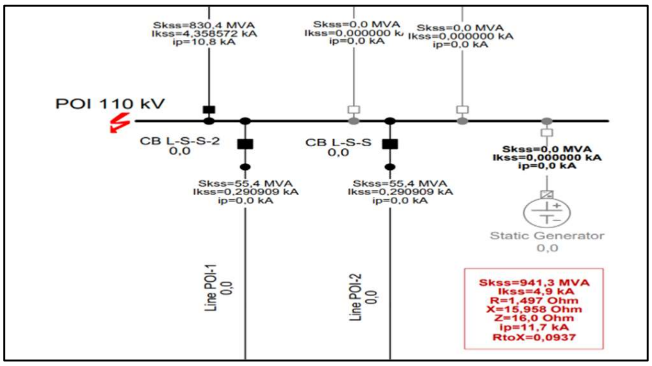

Fig. 11: Simulation results of the current network.

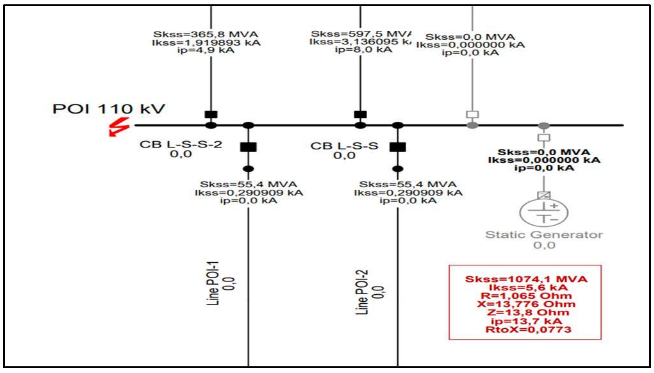

Fig. 12: Simulation results after adding one line on bus 4.

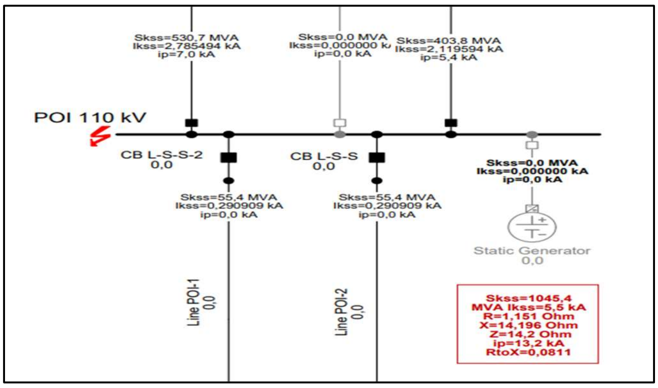

Fig. 13: Simulation results after adding one line on bus 3.

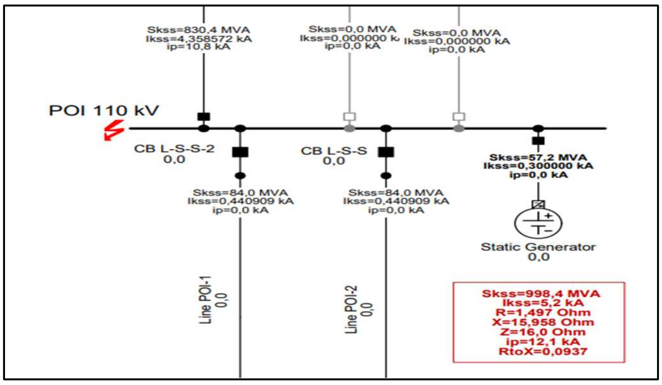

Fig. 14: Simulation results after adding BESS only.

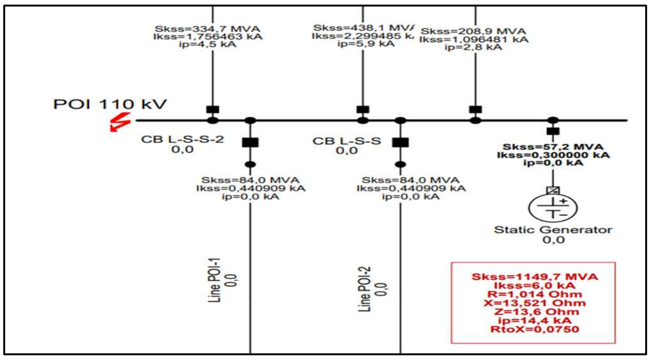

Fig. 15: Simulation results after adding one line on bus 3, 4 and BESS.

TABLE 5.: SCR WITH DIFFERENT GRID CONFIGURATION

No.	Scenario	SCR
1	Existing situation	9.41
2	Additional new transmission line between POI and Bus 4	10.74
3	New line between POI and Bus 3	10.45
4	New BESS at POI	9.998
5	New line between POI and Bus 3, between POI and Bus 4 and new BESS at the POI.	11.49

V. RECOMMENDATIONS

To inject the maximum power in both static and dynamic stability, the grid R/X value after the connection of SPP should be in range of 0.2. To increase the SCR of the POI the design and configuration of the grid should be upgraded. This point is critical in terms of dynamic stability. The solar PV plant can lose generation in case of voltage and frequency deviation below the limits of inverter protection. To improve the SCR at the POI the various scenarios are performed and provided in table 5. Nowadays the connection of BESS with solar PV plant is the main topic. The BESS connected at the same point with solar PV plant can improve the reliability of the grid. On the grid side the system can be upgraded with the new transmission lines to improve the SCR at the POI. The study demonstrates both from grid side and from the Solar PV plant side to improve the SCR at the POI.

VI. CONCLUSIONS

The impact of grid Impedances and strength on the utility-scale PV system has been analyzed. The maximum power transfer capability depends on many factors such as SCR, R/X, PCC voltage amplitude. The simulation and mathematical results verified that for the inductive grid the increasing of SCR to be greater than 5 and the R/X is 0.2 are recommended to obtain the maximum power of the grid. While and resistive grid situation, increasing the voltage at the PCC to be more than rated voltage is suitable for power transmission. Moreover, adding more transmission lines between the buses has a significant impact of increasing the SCR. From the solar side adding a BESS enhanced the system's short circuit power which is increasing the SCR as well. The effectiveness of the model has been verified.

ACKNOWLEDGMENT

This work was supported by Deanship of Scientific Research, King Saud University, Riyadh, Saudi Arabi.

REFERENCES

[1] Enas Taha Sayed,Abdul Ghani Olabi,Abdul Hai Alami,Ali Radwan,Ayman Mdallal,Ahmed Rezk andMohammad Ali Abdelkareem, "Renewable Energy and Energy Storage Systems"

[2] Liang Huang, Chao Wu, Dao Zhou and Frede Blaabjerg "Impact of Grid Strength and Impedance Characteristics on the Maximum Power Transfer Capability of Grid-Connected Inverters"

[3] Egea-Alvarez, A.; Fekriasl, S.; Hassan, F.; Gomis-Bellmunt, O. "Advanced vector control for voltage source converters connected to weak grids" IEEE Trans. Power Syst. 2015, 30, 3072–3081.

[4] Givaki, K.; Chen, D.; Xu, L. "Current Error Based Compensations for VSC Current Control in Weak Grids for Wind Farm Applications" IEEE Trans. Sustain. Energy 2018, 10, 26–35.

[5] Li, Y.; Fan, L.; Miao, Z. "Stability Control for Wind in Weak Grids" IEEE Trans. Sustain. Energy 2019, 10, 2094–2103.

[6] Brown, Tom. "Transmission network loading in Europe with high shares of renewables." IET Renewable Power Generation 9, no. 1 (2015): 57-65.

[7] Gerd Küpper, "Power market design choices with high shares of intermittent renewables", CIRED 2020 Berlin Workshop (CIRED 2020).

[8] Khazaei, Javad, Peter Idowu, Arash Asrari, A. B. Shafaye, and Lakshan Piyasinghe. "Review of HVDC control in weak AC grids." Electric power systems research 162 (2018): 194-206.

[9] Zhou, Jenny Z., and Aniruddha M. Gole. "VSC transmission limitations imposed by AC system strength and AC impedance characteristics." (2012): 06-06.

[10] Shahil Shah, Przemyslaw Koralewicz, Robb Wallen, and Vahan Gevorgian "the Impedance Characterization of Utility-Scale Renewable Energy and Storage Systems".

[11] Yanghong Xia, Yonggang Peng and Wei Wei "Different Influence of Grid Impedance on Low- and High-frequency Stability of PV Generators," November 11, 2019.

[12] YiMing Tu, Jinjun Liu, Teng Liu and Xiangpeng Cheng "Impedance-Based Stability Analysis of Large-Scale PV Station under Weak Grid Condition Considering Solar Radiation Fluctuation" October, 2018.

[13] Elias Kaufhold, Jan Meyer and Peter Schegner "Impact of grid impedance and their resonance on the stability of single-phase PV-inverters in low voltage grids" July 30, 2020.

[14] Collins, Lyle, and J. K. Ward. "Real and reactive power control of distributed PV inverters for overvoltage prevention and increased renewable generation hosting capacity." Renewable Energy 81 (2015): 464-471.

[15] Yang, Dongsheng, Xiongfei Wang, Fangcheng Liu, Kai Xin, Yunfeng Liu, and Frede Blaabjerg. "Adaptive reactive power control of PV power plants for improved power transfer capability under ultra-weak grid conditions." IEEE Transactions on Smart Grid 10, no. 2 (2017): 1269-1279.

[16] Weckx, Sam, and Johan Driesen. "Optimal local reactive power control by PV inverters." IEEE Transactions on Sustainable Energy 7, no. 4 (2016): 1624-1633.