Understanding the Effects of Reduced Short-Circuit Capacity and Inertia on Voltage Fluctuations and Harmonics

Eliot Jiménez-Ortega and Surya Santoso
The University of Texas at Austin
Austin, USA

Robert F. Arritt
Electric Power Research Institute
Palo Alto, USA

***Abstract*—The shift from synchronous generators to inverter-based resources (IBRs) in modern power systems entails several technical challenges, such as reduced short-circuit capacity (SCC) and loss of mechanical inertia. These changes not only negatively impact grid stability but can also deteriorate the power quality of the system. IBRs can also compromise the power quality of the grid due to their inherent harmonic emissions and by amplifying background harmonics. Additionally, voltage variations produced by highly fluctuating loads can become more pronounced in systems with reduced SCC. This paper investigates how reduced system inertia and SCC impact the power quality by evaluating harmonic distortion and voltage-fluctuation severity across multiple system scenarios. First, the harmonic short-circuit capacity metric, SCC(h), is introduced to assess the susceptibility of a bus to distortion at specific harmonic orders. Time-domain simulations demonstrate that neither changes in inertia nor variations in SCC directly determine the total harmonic distortion (THD) caused by background harmonics. Instead, the resulting THD depends on the impedance interactions between the interconnected resource and the network, and SCC(h) provides a reliable indicator of harmonic performance. The results further indicate that reduced SCC substantially increases the severity of voltage fluctuations caused by a highly variable load, whereas changes in inertia have a negligible impact.**

***Index Terms*—power quality, inertia, short-circuit capacity**

I. Introduction

The increasing penetration of inverter-based resources (IBRs) in electric power systems is transforming the grid by replacing conventional thermal generation with renewable sources, such as solar and wind. As synchronous generators (SGs) are supplanted, dependency of the grid on IBRs entails multiple technical challenges. For instance, replacing a SG with a large PV plant can significantly reduce the system's short-circuit capacity (SCC) and inertia. This reduction occurs due to the low short-circuit current contribution and lack of rotating components of inverters [1], which can compromise the stability of the system. Additionally, impedance interactions between the IBR and the system can amplify background harmonics at the point of common coupling (PCC), further contributing to harmonic distortion [2].

In this sense, the integration of voltage-fluctuating loads, such as electric arc furnaces (EAFs), in weak power systems can introduce significant power quality challenges. EAFs, widely used in steel production, are highly non-linear loads that generate considerable voltage fluctuations due to the irregular discharge of their electrodes [3]. These fluctuations can be more severe in systems with reduced short-circuit capacity [4], which may result from replacing synchronous generators with IBRs. For this reasons, understanding how changes in system inertia and short-circuit capacity affect power quality remains an active area of research.

This paper investigates the impact of variations in inertia and short-circuit capacity on the power quality performance of an electric system. First, the role of inertia and SCC in voltage fluctuation severity and harmonic distortion is examined. Next, the harmonic short-circuit capacity metric, SCC(h), is introduced to assess the susceptibility of a bus to distortion at specific harmonic orders. The harmonic performance is then assessed considering variations in inertia and SCC in a representative power system model simulated in EMTP, where both a SG and a PV system of equal capacity are incorporated individually. The findings confirm that total harmonic distortion is not directly dictated by inertia or SCC but by the impedance interaction between the generator and the system. In this regard, SCC(h) provides a reliable metric of harmonic performance. Finally, it is demonstrated that higher SCC significantly reduces the voltage fluctuation severity from a highly-fluctuating load, whereas inertia variations have a negligible impact.

The remainder of this paper is organized as follows. Section II analyzes the effects of inertia and short-circuit capacity on voltage fluctuations and harmonic distortion. Section III introduces the concept of harmonic short-circuit capacity to assess the susceptibility to distortion at a given bus. Section IV compares the power quality performance of a system with modified inertia and short-circuit capacity by evaluating the response to background harmonics distortion and voltage fluctuations caused by an electric arc furnace. Finally, Section IV concludes this paper.

II. Effects of Inertia and Short-Circuit Capacity on Voltage Fluctuation and Harmonic Distortion

This section revisits the fundamental concepts of inertia and short-circuit capacity for synchronous generators and inverter-based resources, and discusses their influence on voltage fluctuations and harmonic distortion.

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A. Inertia

The rotors of synchronous generators store kinetic energy that resist changes in their angular speed, providing mechanical inertia to the power system [5]. Following a disturbance, this stored energy is exchanged with the grid to balance mechanical and electrical torques, which limits the initial rate of frequency deviation [6], [7]. Conversely, inverter-based generators lack physical inertia and therefore cannot inherently exchange kinetic energy with the system [8]. PV systems, for example, have no rotating mass and provide no natural inertial response; however, they can adopt control strategies such as virtual inertia to mimic its behavior.

For a given SG, the inertia is commonly normalized using the inertia constant, H, defined as

$$H \;=\; \frac{1}{2}\cdot\frac{J\omega_{\rm s}^2}{S_{\rm VA}}, \tag{1}$$

where J is the moment of inertia of the rotating mass in the generator, $\omega_{\rm s}$ is the synchronous angular speed, and $S_{\rm VA}$ is the generator's power rating. The units of H are seconds, representing the time a generator can provide the rated power using only the kinetic energy stored in its rotating mass [9]. Similarly, the swing equation of a SG is as follows:

$$2H\frac{d\omega}{dt} \;=\; P_{\rm m}-P_{\rm e}, \tag{2}$$

where $P_{\rm m}$ and $P_{\rm e}$ are the electrical and mechanical power of the generator and ω is the rotor speed. A larger H leads to a lower rate of change in speed [10].

Although inertia influences the dynamic behavior of synchronous machines, its effect is primarily related to the system frequency, not the voltage. Equation (2) describes the balance of mechanical and electrical power through rotor acceleration and deceleration, which associates inertia directly to the rate of change of frequency. Conversely, voltage is mainly governed by network impedance, reactive power balance, and excitation control. Therefore, the swing equation does not directly regulate voltage magnitude, and inertia plays only a secondary role in mitigating voltage fluctuations. As a result, while higher inertia reduces the rate of frequency deviation, its effect on short-term voltage performance is limited. Inertia also has no influence on steady-state harmonic distortion since these power quality phenomena do not interact with the system's inertial response [11].

B. Short-Circuit Capacity

The short-circuit capacity at a bus depends on the short-circuit level (SCL), defined as the current delivered during a three-phase fault. Whereas synchronous generators can contribute fault currents on the order of 4 p.u., inverter-based resources are typically limited to approximately 1.2 p.u. [12]. Consequently, replacing synchronous units with IBRs reduces both system inertia and available short-circuit capacity.

Following a three-phase fault, the SG fault current rises rapidly and then decays according to the subtransient and transient time constants [6]. Its peak value depends primarily on the prefault voltage, subtransient reactance, and rotor position. Because this interval lasts only a few milliseconds, rotor speed is assumed to be constant, and inertia has negligible influence [6]. Therefore, inertia does not affect the peak fault current nor the resulting SCC.

In this sense, to understand how SCC influences voltage fluctuations, it is useful to revisit its fundamental definition. In a balanced three-phase system, the SCC at a bus is given by the rated rms line-to-line voltage $V_{\rm LL}$ and the Thevenin reactance $X_{\rm th}$:

$$\text{SCC} = \sqrt{3}V_{\rm LL}I_{\rm f} = \frac{V_{\rm LL}^2}{X_{\rm th}}. \tag{3}$$

where $I_{\rm f}$ is the three-phase fault current. Since SCC is inversely proportional to the Thevenin impedance, a high SCC indicates a strong, stiff grid with low $X_{\rm th}$, resulting in small voltage deviations ΔV during load changes. In contrast, a low SCC corresponds to a weak grid with higher $X_{\rm th}$, which make the system more sensitive to load variations.

While the influence of SCC on voltage fluctuations is straightforward, its relationship to harmonic distortion is not strictly monotonic [13]. The SCC determines how current harmonics translate into voltage distortion at the PCC. In weak grids, higher impedances can amplify background harmonics, and shifts in network impedance may align resonance frequencies with dominant harmonic orders, increasing sensitivity to both background- and IBR-generated harmonics [14]. However, a high SCC does not guarantee low distortion, as the impedance interaction between system components can still cause localized amplification even in strong grids. Thus, SCC alone is insufficient to characterize the harmonic distortion risk at a given bus.

III. Harmonic Short-Circuit Capacity

This section introduces the concept of harmonic short-circuit capacity, SCC(h), a normalized metric that quantifies the strength of a bus at a specific harmonic order.

Assume a power system with background harmonics, represented by the equivalent circuit in Fig. 1. The impedance seen at the PCC at harmonic order h is

$$Z_{\rm pcc}(h) = Z_{\rm th}(h) \;\|\; Z_{\rm sys}(h),$$

where $Z_{\rm th}(h)$ is the grid Thevenin impedance and $Z_{\rm sys}(h)$ denotes the impedance of the downstream network, comprising lines, transformers, and capacitor banks, at the same harmonic frequency.

For a background harmonic of order h, the resulting voltage distortion at the PCC is

$$V_{\rm pcc}(h) = V_{\rm bkg}(h)\frac{Z_{\rm sys}(h)}{Z_{\rm sys}(h)+Z_{\rm th}(h)}. \tag{4}$$

Equation (4) shows that the amplification of upstream background distortion is dictated by the relative magnitude of $Z_{\rm sys}(h)$. Since $Z_{\rm sys}(h)$ varies with voltage level and network configuration, it is useful to define a normalized metric that provides an indication of harmonic stiffness across different

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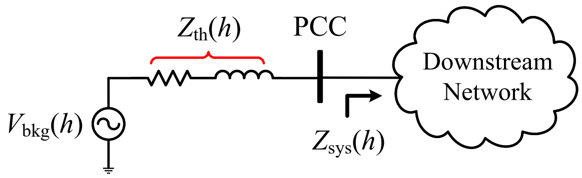

Fig. 1. Equivalent grid representation of the impedance interaction between the power system and the downstream network at the PCC.

buses and voltage levels. Accordingly, the *harmonic short-circuit capacity* is defined as

$$\mathrm{SCC}(h) = \frac{V_{\mathrm{LL}}^2}{|Z_{\mathrm{pcc}}(h)|}, \tag{5}$$

where V_{LL} is the rated fundamental line-to-line voltage at the bus. This expression generalizes the conventional short-circuit capacity to harmonic frequencies and provides a measure of grid strength at order h. Note that in (5), the rated fundamental voltage is employed to provide a consistent normalization of $\mathrm{SCC}(h)$ across the system, rather than relying on the highly variable and frequently negligible harmonic voltage of order h.

From (4), for a fixed background distortion V_{bkg}^h, the resulting harmonic voltage appearing at the PCC is inversely proportional to the harmonic SCC:

$$\left|V_{\mathrm{pcc}}(h)\right| \propto \frac{1}{\mathrm{SCC}(h)}. \tag{6}$$

Thus, a lower harmonic SCC increases the susceptibility of the PCC to amplification of upstream background harmonics, whereas a higher $\mathrm{SCC}(h)$ improves harmonic attenuation and reduces the sensitivity of the bus to harmonic distortion.

IV. Power Quality Assessment

This section evaluates the power-quality performance of a representative power system under the interconnection of either a SG or a PV system. Harmonic behavior is assessed through time-domain simulations in which the THD resulting from background harmonics is quantified and compared against the harmonic SCC metric, $\mathrm{SCC}(h)$. In addition, a voltage-fluctuating load is introduced, and the resulting voltage fluctuation severity is examined for both interconnection scenarios.

A. Test Cases

Consider the EMTP simulation model shown in Fig.2. It represents a test system which consists of a 150 MW, 30 Mvar load connected to the power system via a 230 kV transmission line, TL1. The power system equivalent is represented using a Thevenin equivalent, and this configuration is referred to as the Base Case. Building on this test system, three additional cases are developed by incorporating a generation resource, either a 200 MW SG or PV Park, interconnected to the system via transmission line TL2. The configuration of each case is summarized in Table I.

The equivalent system is assumed to have a total inertia H_{sys} determined by the generators online. Thus, ΔH denotes the increase in system inertia contributed by the generation resource in each case, as listed in Table II. The same table shows the SCC measured at Bus L for each case. As expected, cases SG-4 and SG-8 show that adding a synchronous generator increases the SCC. Moreover, increasing the SG inertia constant from $H = 4$ s to $H = 8$ s produces negligible

TABLE I
Test Cases Summary

Case	Description
Base	A 153 MVA load is connected to the power system via TL1
SG-4	Base case + 200 MW SG with inertia H = 4 s connected to Bus L via TL2
SG-8	Base case + 200 MW SG with inertia H = 8 s connected to Bus L via TL2
PV	Base case + 200 MW PV park connected to Bus L via TL2

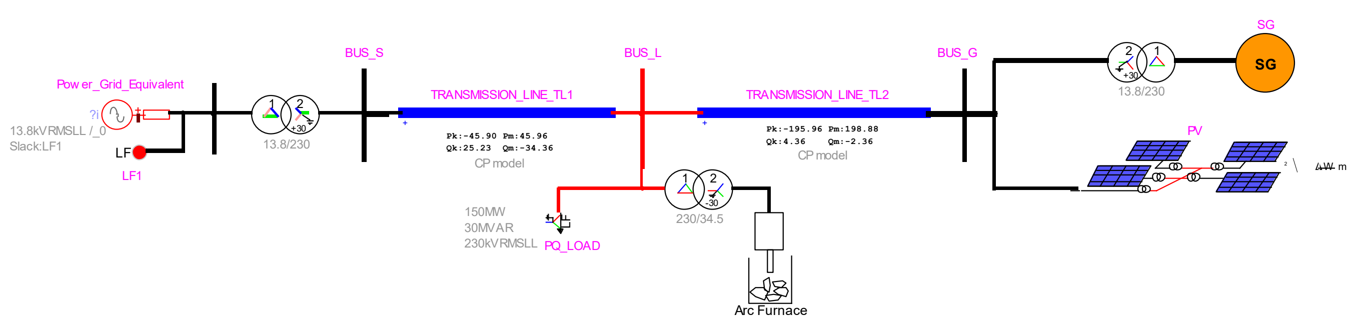

Fig. 2. EMTP simulation model of a three-node electric power system. In the Base Case, a 150 MW, 30 Mvar load is connected to the Thevenin equivalent of the power system via a 230 kV transmission line (TL1). SG-4 and SG-8 cases incorporate a 200 MW, 13.8 kV synchronous generator interconnected to Bus L via the transmission line TL2. In PV case, a 200 MVA, 34.5 PV system is interconnected to to Bus L through the transmission line TL2. The parameters of both TL1 and TL2 are R = 2.43×10^{-2} Ω/km, L = 0.5×10^{-2} mH/km, and 0.0126 μF/km. The length of TL1 and TL2 is 160.93 km and 40.23 km, respectively.

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TABLE II
TOTAL HARMONIC DISTORTION ASSESSMENT AND SCC(h) AT BUS L

Case	Inertia Increment ΔH [s]	SCC	5^{th} Harmonic Order		7^{th} Harmonic Order		11^{th} Harmonic Order	
			SSC(h)	THD	SSC(h)	THD	SSC(h)	THD
Base	0	725	181 MVA	3.90%	91 MVA	4.44%	31 MVA	11.58%
SG-4	4	1242	128 MVA	5.47%	176 MVA	3.08%	593 MVA	0.47%
SG-8	8	1242	128 MVA	5.47%	176 MVA	3.08%	593 MVA	0.47%
PV	0	773	432 MVA	1.39%	703 MVA	0.65%	697 MVA	0.49%

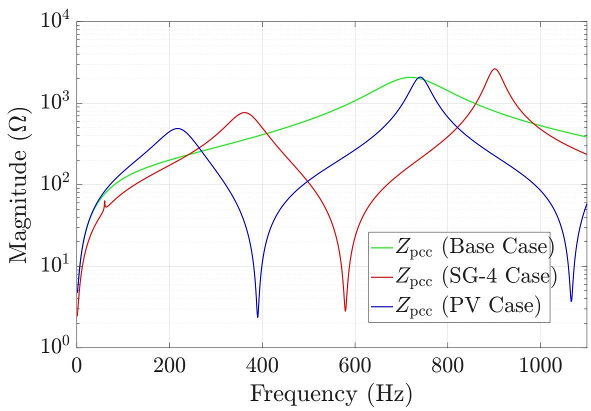

Fig. 3. Impedance scans of Base, SG-4, and PV cases at Bus L. The frequency response of the system changes significantly with the incorporation of either the SG or the PV system.

changes in SCC, consistent with the analysis presented in Section II-A.

B. Harmonic Distortion Analysis

This subsection evaluates the harmonic performance of the four cases described in Table II. First, a frequency scan at Bus L of the Base, SG-4, and PV cases is shown in Fig. 3; SG-8 is omitted because its response is identical to SG-4. It is evident that adding the line and generator in SG-4 and PV cases modifies the impedance profile of the Base Case.

A background harmonic distortion of 5% of the nominal voltage at the 5^{th}, 7^{th}, and 11^{th} orders (one at a time) is superimposed in the grid equivalent source. The corresponding SSC(h) and resulting THD for each case are reported in Table II. The results indicate that the harmonic SSC(h) provides a more accurate measure of harmonic distortion risk than the conventional SCC, which confirms the non-monotonic relationship between grid strength and harmonic distortion. For instance, the cases with highest short-circuit capacity (SG-4 and SG-8) exhibit higher distortion at the 5^{th} harmonic, whereas the PV case produces lower distortion at the critical low-order harmonic frequencies, despite its reduced SCC.

C. Voltage Fluctuation Analysis

To evaluate the performance of each case in terms of voltage fluctuations severity, the load at Bus L is replaced with a 34.5 kV, 70 MW electric arc furnace. The incorporation of this load results in significant voltage fluctuations of varying severity observed across the 4 test cases. Fig.4 shows the RMS voltage of phase A at Bus L for the Base, SG-4, and PV cases. It is visually evident that the voltage fluctuations become more severe in systems with reduced short-circuit capacity (Base and PV).

The severity of the voltage fluctuations can be quantified in each case by means of the coefficient of variation (CV):

$$\mathrm{CV} = \frac{\sigma}{\mu} \times 100\%, \tag{7}$$

where σ denotes the standard deviation, and μ represents the mean value of the RMS voltage at any given Bus. Note that the coefficient of variation is expressed as a percentage.

The CV was computed for the RMS voltage of phase A in each case. The results are shown in Table III, which also presents the SCC at Bus L and the system's inertia. It is confirmed that the fluctuations are less severe at Bus S, in comparison to Bus L. This is explained by the electrical distance between Bus S, where the power system is connected, and Bus L, where the EAF is connected. Additionally, as expected, the CV is significantly higher in the Base and PV cases and less pronounced in the SG cases, due to the differences in the short-circuit capacity. Finally, the nearly identical CV values observed in the SG-4 and SG-8 cases confirm that increasing generator inertia has a negligible effect on the severity of voltage fluctuations.

Lastly, two additional cases are introduced to assess the effect of SCC variations on voltage fluctuations. In case SG-4-A, reducing the line impedance of TLM1 ($R = 1.5 \times 10^{-2}\,\Omega/\mathrm{km}$, $L = 0.5 \times 10^{-2}\,\mathrm{mH/km}$) increases the SCC at Bus L

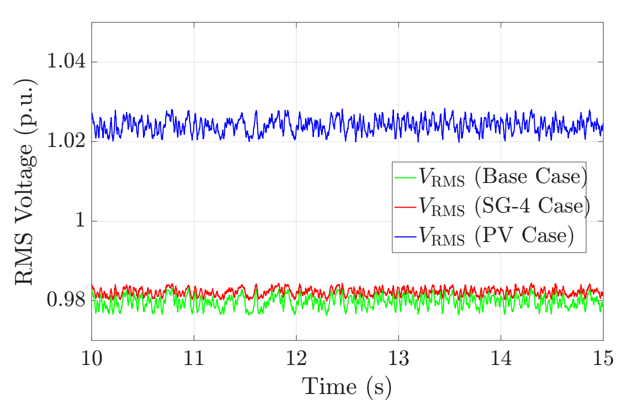

Fig. 4. Voltage fluctuations caused by the EAF are evident in the RMS voltage at Bus L. The PV and Base cases present more pronounced fluctuations than the Base case due to their lower SCC.

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TABLE III
VOLTAGE FLUCTUATIONS ASSESSMENT

Case	System Inertia Increment ΔH [s]	SCC Bus L [MVA]	CV Bus S [%]	CV Bus L [%]
Base	0	725	0.1350	0.1633
SG-4	4	1,242	0.0782	0.0963
SG-8	8	1,242	0.0783	0.0965
PV	0	773	0.1427	0.1713

to 1,335 MVA. Conversely, in case SG-4-B, increasing the impedance ($R = 2.7 \times 10^{-2}\,\Omega/\text{km}$, $L = 2.8 \times 10^{-2}\,\text{mH}/\text{km}$) lowers the SCC to 890 MVA.

Table IV summarizes the SCC and CV results for cases SG-4-A and SG-4-B, with case SG-4 included for comparison. The results show that, for SGs with identical inertia, variations in short-circuit capacity significantly influence the severity of voltage fluctuations at both Bus S and Bus L. The case with reduced SCC, SG-4-B, presents significantly higher CV values at both buses while they remain small in the strongest case, SG-4-A.

TABLE IV
VOLTAGE FLUCTUATIONS ASSESSMENT

Case	System Inertia Increment ΔH [s]	SCC Bus L [MVA]	CV Bus S [%]	CV Bus L [%]
SG-4-A	4	1,335	0.0705	0.0865
SG-4	4	1,242	0.0782	0.0963
SG-4-B	4	890	0.0992	0.1242

V. CONCLUSION

This paper investigated the impact of reduced short-circuit capacity (SCC) and inertia in the power quality performance of an electric system. The presented analysis examined how harmonic distortion and voltage-fluctuation severity are influenced by variations in SCC and inertia introduced by the interconnection of a synchronous generator and a PV system.

First, the harmonic short-circuit capacity metric, $\text{SCC}(h)$, was introduced to quantify the susceptibility of a bus to distortion at a given harmonic order. Time-domain simulations showed that reducing the inertia and the SCC at a given bus does not directly determine the total harmonic distortion caused by background harmonics. Instead, the resulting THD is dictated by impedance interactions between the interconnected resource (SG or PV) and the network. The proposed $\text{SCC}(h)$ metric accurately predicts the distortion at each harmonic order, demonstrating its effectiveness as a reliable indicator of harmonic performance.

The results also confirmed that reduced SCC values substantially increase the severity of voltage fluctuations produced by an electric arc furnace, a highly voltage-fluctuating load, whereas increasing or decreasing the inertia constant H has a minimal influence. This highlights that SCC plays a more dominant role than inertia in mitigating short-duration voltage fluctuations. These findings, based on a representative three-node power system, provide a foundation for future studies focused on power-quality impacts in increasingly inverter-dominated grids.

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