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# The Impact of Large Scale Photovoltaic Systems on the Harmonic Increase in Distribution Networks

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**Abstract**

The significance of electricity generation by photovoltaic (PV) systems comes from the direct conversion of light into electrical energy. Although such a system is widely used in a small scale, the tendency to apply it in a large scale is gaining ground day after day. However, large generation systems of this type are associated with their own problems arising when they are connected to the national grid. One of these problems is the generation of harmonics from control and power conversion devices included in Photovoltaic system. In the present paper, the mutual impact between large-scale photovoltaic generation systems and electrical grid will be studied in terms of power quality. This requires building a model of large-scale photovoltaic system, connecting it to the grid and testing it under various conditions. Several scenarios will be proposed for the operation of such system taking into consideration the penetration level of solar system, loading levels and load composition of the examined grid. The key elements, exciting harmonic problem, will be identified in the present work and the issues related to such phenomenon will be studied in parallel with other operational patterns dominating in distribution grids. As being relatively intermittent source of energy, photovoltaic will have some means of protection and control which will be considered as parts of this system. The present paper also combines the results obtained from Simulink into LabVIEW which provides a reliable way in analyzing the variation of parameters governing the harmonic behavior. After connecting PV arrays to the grid, the harmonic level increases up to 13.3% in the case of 150 kW PV systems because of the power electronic devices in operation. The effects of the solar radiation and the operating temperature of PV modules on the harmonics are investigated and modeled. The simulations show that the total harmonic distortion is 13.22 %, 13.30%, and 13.40% at T= 30°C, 25°C and 20°C, respectively.



**Keywords:** *Photovoltaic, generation, solar, harmonics, distribution and grid*.

## 1. Introduction

The continuous increase in oil prices and the frequent warnings of limited resources and reserves of such fuel have pushed the decision-makers in energy industry to accelerate the use of renewable energy, especially the wind and solar. The intermittent nature of wind makes it unfavorable in many locations, whereas electricity generation by Photovoltaic (PV) is more stable and reliable. Therefore, the installation of PV arrays is not limited to residential load at low voltage, but it extends to include the medium voltage at utility scale. The introduction of this new approach of electricity generation system has its own influence on the performance of distribution networks including the power quality of the supply.

The summation of all harmonic components of the PV voltage or PV current waveform compared to the fundamental component of the voltage or current wave is defined as the Total Harmonic Distortion. The presence of a high value of THD is one of the main indices of power quality poorness. On the other hand, the large scale of PV integration into distribution network needs a robust system of control devices, converting equipment and protective relaying. With the increase of non-linear loads within these systems, the harmonic penetration level will be augmented. Therefore, one of the vital concerns of distribution utilities is to take the required precautions and to conduct the necessary research to be immune from the side effects of PV large scale distribution.

Although the main concern in PV development and application was on the improvement of cells efficiency, several researchers were interested in PV integration with electric grid [1-3]. Another group of workers has tried to use a suitable simulator to study photovoltaic generation systems and connect them with the grid [4], whereas some investigators have attempted to reduce the harmonic impact by applying new topology for PV generation systems integrating current harmonic compensation by using two inverters. The first one was with a feedback loop to compensate the low order harmonics, and the second

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one with a feed forward loop for compensating high order harmonics [5-6].

Despite the importance of the worksabove, the research of harmonic generation associated with large scale PV systems is still in need for more investigation and further study. In the present work much attention is paid to individual harmonics in addition to the THD for existing distribution systems. In comparison with other works, the present paper demonstrated and tested a model of large scale PV system. In addition, several scenarios were proposed for the operation of such system taking into consideration the penetration level of solar system, loading levels and load composition of the examined grid.

## 2. System Model and Data Collection

The present work was started by building a large scale PV generation model using Simulink to provide a power up to 150 kVA at maximum power point. The next step was to set the parameters of a radial feeder chosen as an example from a real distribution network of Irbid District Electrical Company- Jordan (IDECO). After that, the jointing process has been made using PWM inverter. In this system, the PV model operates as a distributed generation feeding the network with electrical supply. The main components included in this model are:

1. Current network configuration before PV connection and the values of normal harmonic distortion (without PV).
2. The existing loads taking into consideration nonlinear ones.
3. Transmission lines and transformers impedances in addition to generation part
4. Boost chopper followed by controlled inverter.
5. PV generation unit with a suitable interface to enter temperature value, insolation and PV module parameters.
6. Measuring and monitoring system for voltage and power values.

The harmonic content was initially known by monitoring the THD in the examined system at the supply point. Then, the PV system was connected through an inverter to determine the influence of such generator on the THD. The analysis is not restricted to one harmonic value; it is also concerned with studying the effect of radiation and temperature variations on different THD values. This approach provided a better prediction for THD value during daily and seasonally variations.

The data used in modeling the radial power system were obtained from (IDECO) and the main components to operate such system were transformers, medium voltage transmission lines and loads. In addition to that, harmonic sources were presented by nonlinear loads with rectifying devices, whereas PV modules were selected from Centrosolara Company, where the S520P36 Ultra module is used. By using LabVIEW, Harmonic analysis interface is built to give brief results about voltage and current harmonic contents, THD and inter harmonics depending on waveforms taken from Simulink results. Figure 1 shows a single line diagram of the examined distribution section.

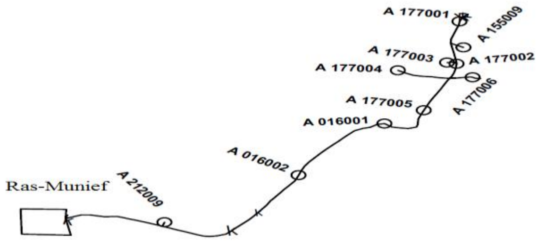


**Figure 1**. Single line diagram of the distribution section

## 3. System Simulation and Results

It is expected that the main source of harmonics during the operation of PV system will be the inverter and the harmonic composition in this case will be a function of its capability to convert the DC output of the solar panels into pure AC sine wave. Therefore, a MATLAB/Simulink interface for solar module parameters was built.

### *3.1. The Harmonic Contents before Connecting PV Arrays*

The examined system was initially simulated with its actual load under normal conditions. The measuring point was selected to be at the beginning of the line, directly after the power source. As illustrated in Figure 2, the simulation results have shown the harmonic contents waveforms of the voltages and currents.

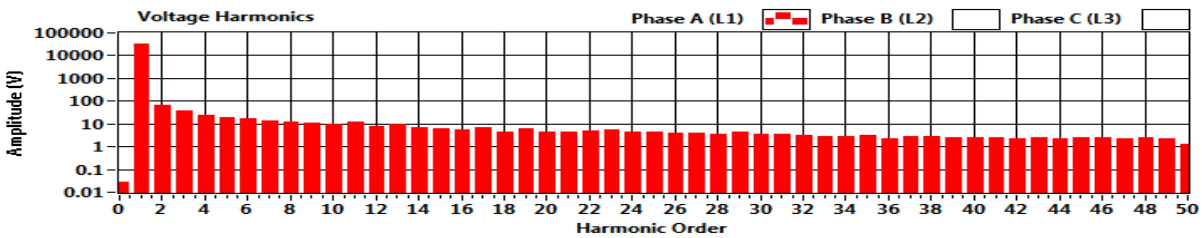


**Figure 2 (a)**. Voltage harmonics shown in phase A

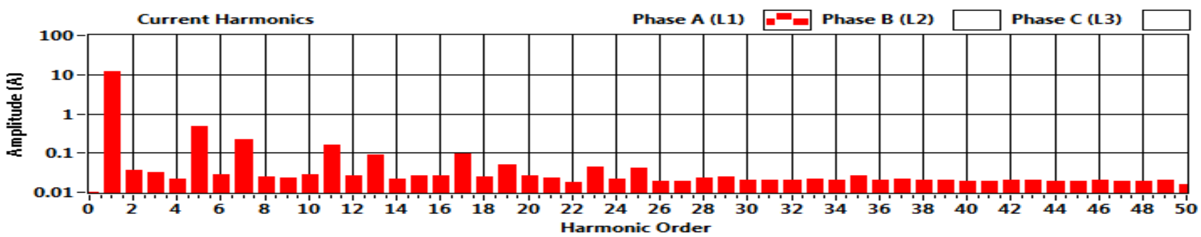


**Figure 2 (b).** Current harmonicsshown in phase A

The $THD_v$ was evaluated by LabVIEW software and found to be 0.58% whereas the $THD_I$ is 4.7%. The significant harmonic orders are the $5^{th}$, $7^{th}$, $11^{th}$, and $13^{th}$ which resulted from the operation of six-pulse converters. This is normal for such a system compared with standard values.

Interharmonicswere also taken in consideration when the analysis was done. Figure 3 illustrates sample of measured current interharmonics.

*3.2. Harmonic Contents after Connecting the PV Generation*

The current-voltage characteristic of PV modules is non-linear and depends on the level of solar irradiance on the surface of the PV modules and their operating temperatures. Therefore, the maximum power point will vary according to the ambient conditions. When the solar irradiance varies at constant temperature, the short-circuit current changes proportionally with the solar irradiance while, the open-circuit voltage changes to a lower extent. However, when the temperature varies at constant solar irradiance level of 1000 W/m2, the open-circuit voltage, in this case, changes in an inverse way with respect to the temperature, whereas the short-circuit current changes to a lower extent. In the operating field, the solar radiance and the temperature change simultaneously which leads to the need to establish test devices. In the PV industry, the standard conditions refer to the temperature of 25°C and to the solar irradiance of 1000 W/$m^2$, as well as to Air Mass (AM) equal to 1.5, at null wind speed. These conditions refer to a day with clear sky and to a surface having an angle of 41.81° with respect to the horizon [7].

The PV is usually connected to the inverter, the operation of which will be the dominant effect on the production of harmonics. This is attributed to the fact that semiconductor devices are the main components of the inverter and, therefore, it is worth giving this element more concentration regardless of its type. The one employed in the present paper is a pulse width modulation (PWM) inverter with operating switching frequency of 5kHz. Step up chopper is also used before the inverter to provide rms voltage at the second side of the inverter. The voltage is then stepped up to 33kV using a step up transformer to match the distribution voltage connection point. Additionally, a Voltage Source Converter control (VSC) is used to achieve constant AC output value from the inverter with the variation of generation values and this improves the operation of such generation system by keeping the voltage level constant. DC-DC boost converter, inverter and VSC control are assumed to operate as constant parameters in the simulation.

*3.2.1. The Effect of Changing of Solar Radiation on Harmonic*

By connecting PV system to the grid, it starts supplying part of the distribution load with the required electrical energy. However, the operation of switches and converting devices from DC to AC will cause a non-pure sinusoidal output signal delivered to the grid. The analysis starts at a high value of insolation (1000W/$m^2$) and then it decreases to illustrate the change of harmonic contents.

The results show that the voltage waveforms have insignificant harmonic distortion compared with that of current waveforms. Figure 4 demonstrates spectrum of current harmonic values in phase A.

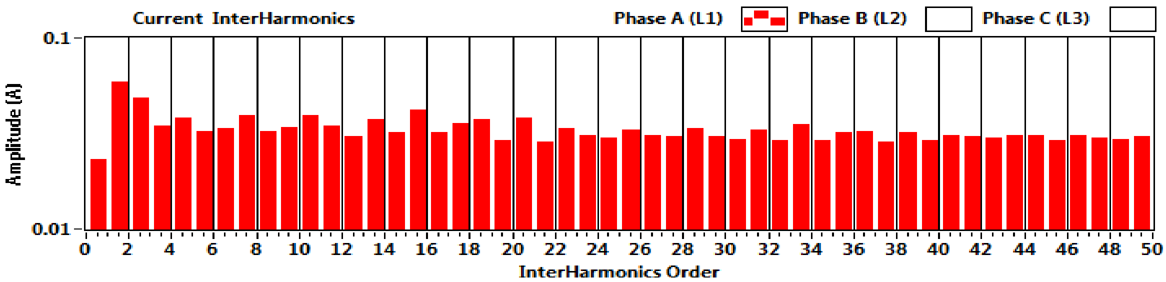


**Figure 3.** Current interharmonics

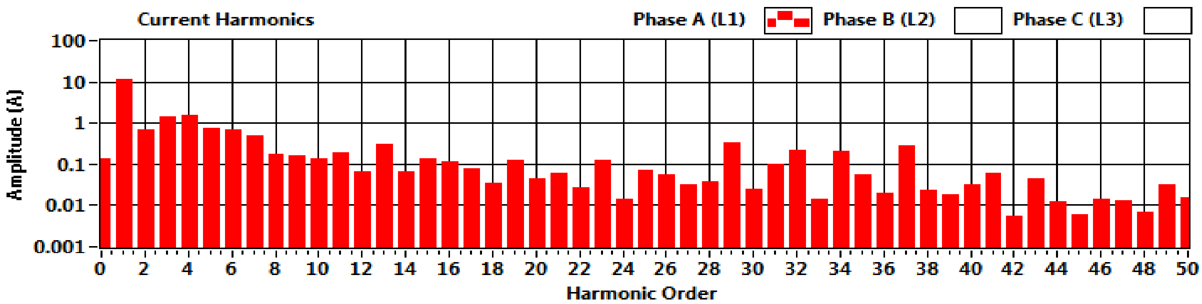


**Figure 4.**Spectrum of current harmonic values in phase A at insulation level of 1000W/$m^2$

 

The resulted THD in current waveforms is 13.3%. This value is much higher than that of the studied system before PV connection.Therefore, the existence of the solar system under normal conditions raised the THD to a very high value. The system was also simulated at 700 W/m$^2$ and 25$^o$C, which is less than the standard value of solar radiation. In order to investigate the effect of low solar radiation on harmonics, the same parameters were assessed. Figure 5 shows current harmonic values in phase A for this case.

The resulted THD in current waveforms is 13.09% at 700W/m2 solar radiation. For 500 W/m2 insolation, the same process was repeated and Figure 6 shows the spectrum of current harmonics in phase A.

*3.2.2. TheEffect of Changing Temperature on Harmonic*

In this part of the work the solar radiation will be considered as a constant and the temperature will be the variable factor. The results will be taken at different values of temperatures namely, 30$^o$C, 25$^o$Cand 20$^o$C. In all cases the solar radiation was assumed to be 1000 W/m$^2$. Figure 7 illustrates the spectrum of current harmonic at temperature of 30$^o$C in phase A.

The resulted THD in current waveforms is 13.3% in this case. Figures 8 and 9 show the spectrum of harmonic current at temperatures of 25oC and 20oC, respectively.

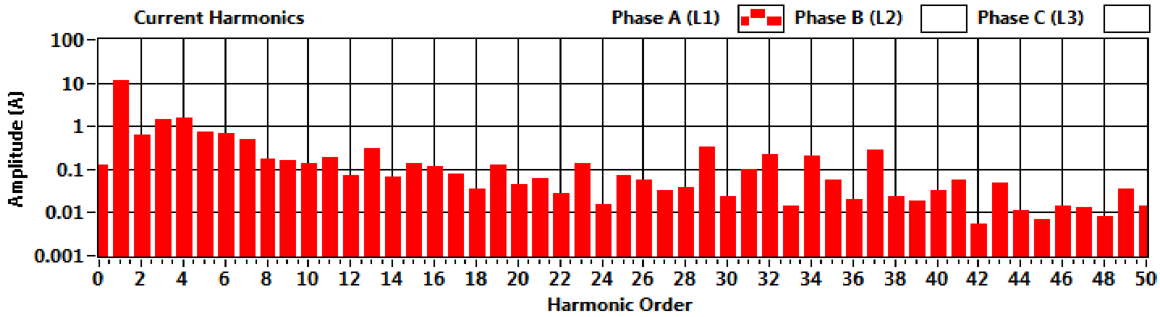


**Figure 5.**Spectrum of current harmonic values in phase A at insulation level of 700W/m$^2$

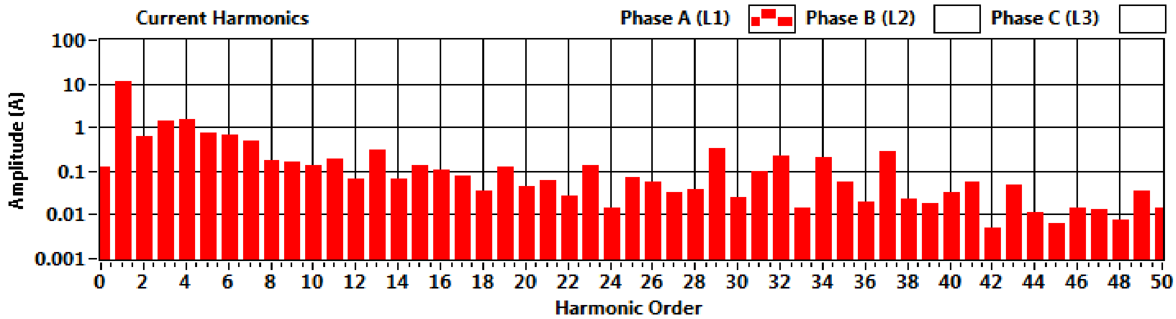


**Figure 6.**Spectrum of current harmonic values in phase A at insulation level of 500W/m$^2$ [THD = 13.07%]

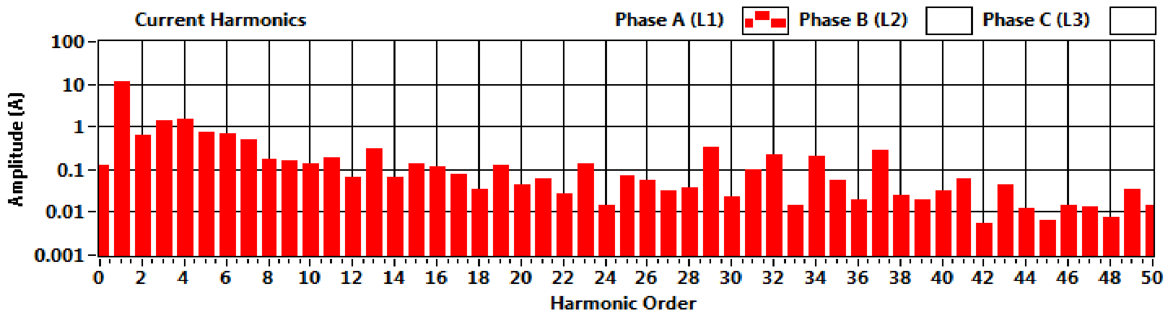


**Figure 7.**Spectrum of current harmonic in phase A at a temperature of 30$^o$C.

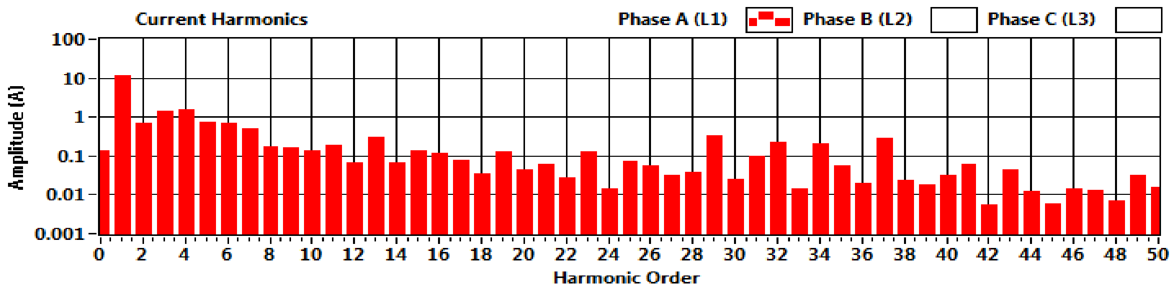


**Figure 8.**Spectrum of current harmonic in phase A at a temperature of 25$^o$C [THD = 13.3%]

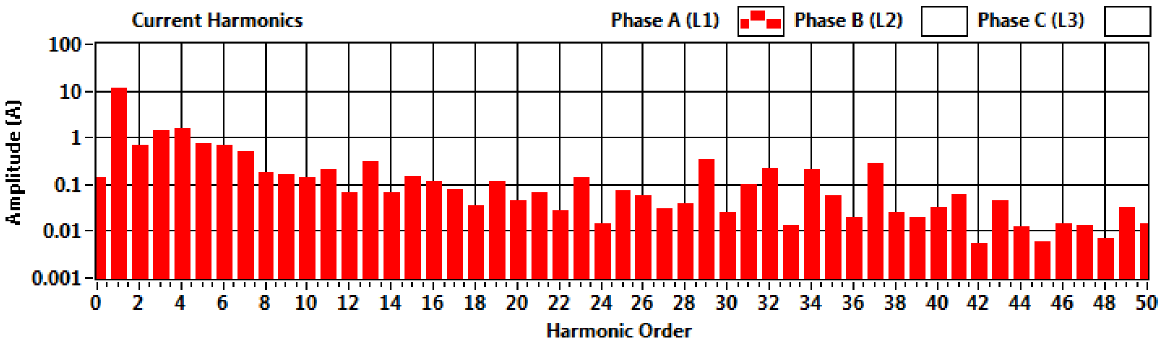


**Figure 9**.Spectrum of current harmonic in phase A at a temperature of 20°C [THD = 13.4%]

## 4. Analysis and Discussion

The employment of high performance simulator, which is based on MATLAB/Simulink program, provides a model that can be easily adopted for various temperature and radiation values to set a precise solar generator model. One of the strong points of the present work is the possibility of taking the waveforms of current and voltages obtained from Simulink and analyze them in another tool (LabVIEW). The latter is well-known as a strong tool in harmonic analysis. This approach provides an accurate and effective way in analyzing the variation of parameters governing the harmonic behavior. It simulates a real power system and adds one of renewable resources to existing grids to monitor the effect of integration.

Before connecting the PV system to the distribution network, the THD was found to be 4.6%. Although this factor is a good indication of harmonic level, it is usually advisable to inspect the individual harmonics. In comparison of the harmonic voltage to the harmonic current values, the latter was more noticeable. Usually, the main source of harmonics is the nonlinear loads in the system. However, after connecting PV arrays to the grid, the harmonic level has shown a significant increase. By installing large amounts of PV arrays (in this case 150 kW), the THD level becomes remarkably high (13.2 %). This value reflects the seriousness of the problem and the high percentage of electronic devices involved. The continuous operation of power electronic devices in the inverter and the currents that are injected to the grid are indicators about the degree of distortion that can be sensed during measurements. Any adjacent load will draw a distorted current and by passing through impedances more distortion can be recorded. With time the system becomes completely "polluted" and the THD gets higher and higher. This high value of THD may affect sensitive controlling systems and loads.

The individual harmonics that appear significantly before adding the PV system were the 5$^{th}$, 7th, 11$^{th}$ and 13$^{th}$. This is attributed to the six pulse power converter used in the loads. After connecting the PV system, the harmonics were increased because the influence of the inverter in the solar generation system. Even harmonics also appear due to the operation of the transformer between PV system and the grid but with small values.

Solar radiation is one of the main parameters that affect the generation level of PV arrays. It appears from the characteristics that the value of output power from PV arrays will increase as the radiation increases. The variation of the solar radiation occurs in a random manner during cloudy days and varies from day to day, which makes the predicting of the exact value of generation a difficult task. However, the model used can provide the flexibility to change the insolation level to any value, which facilitates prediction the generated power and its influence on the harmonics.

The slight decrease in THD with decreasing the radiation is attributed to the decrease in the value of generated power, and consequently, a less distorted current will be delivered to the grid.

One of the most important factors that affect the operation of all electrical devices is the temperature. The excessive increase in temperature causes less efficient operation of devices in general. Here in PV arrays, the temperature is one of the main dominant factors that affect the generated power by variation the efficiency of PV cells. When running the simulation at a temperature of 30°C, the THD was found to be 13.22 % and then, at 25°C it is found to be 13.3 %. Finally, the THD was 13.4% at 20°C. Therefore, it is not difficult to notice that the temperature decrease causes an increase in the THD in the system. When the temperature increases, the generated power will decrease, so less current delivered to the grid and then less distorted signal presented in the system.

## 5. Conclusions

The present work has revealed several conclusions. Firstly, the distribution systems, which will be treated as incubators for PV generation, have already some harmonic problems. Although these problems are still not dangerous, but they are in a continuous increase and they might cause serious problems in the future.Secondly, the present work has clearly illustrated that the connection of large scale PV to the distribution grid will significantly increase the THD level and will augment the problem of distribution system performance. The obtained level of THD exceeds the permissible limit for normal operating systems. Finally, the impact of solar radiation and temperature on the harmonic spectrum and THD level was clear. The increase in radiation and the reduction in temperature lead to an increase in the output of the PV, which means an increase in the distorted current and an increase in the harmonic level. However, the change in THD was small in some cases due the selected range of variation.

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