MITIGATING OF VOLTAGE SAG/SWELL BY SERIES VOLTAGE REGULATOR FOR A DISTRIBUTION TRANSFORMER IN DISTRIBUTION GRID SYSTEM

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Abstract— The power quality (PQ) requirement is one of the most important issues for power system. The main problems of the power quality like voltage sags/swells in low voltage distribution systems and on the transmission side due to sensitive loads. There are different methods to compensation of voltage sag and swell, one of the most popular methods of sag and swell compensation is a series voltage regulator for a distribution transformer which addresses power quality issues in the electrical power distribution system. The proposed system is comprised of a line frequency transformer connected to a power electronic converter which is auto-connected on the secondary side. This auto-connection is facilitated by use of a high-frequency or medium frequency transformer.

The proposed system has a wide range voltage compensation that can correct both the sags and swells of the grid voltage. A simplified strategy to compensate for voltage sags and swells on the grid side, by providing continuous ac voltage regulation, is discussed. When a voltage sags or swells occur, the power electronic converter generates a compensating voltage, which is vector-added to the grid voltage in order to regulate the output voltage supplied to the load. The proposed system satisfies needs of smart distribution grids in terms of improved availability, equipment protection, and resilience. Detailed analysis is provided with MATLAB/SIMULINK results in order to validate the effectiveness of the proposed system.

Index Terms— Distribution transformer, phase-shift modulation, ride-through system, voltage sag/swell compensation.

I. INTRODUCTION

Power quality is an important issue for distribution network companies. They must guarantee the electricity supply for the customers, while fulfilling certain quality requirements. Public institutions are involved in this topic as well. There are European standards and, usually, every country has specific regulations for power quality too. One of these requirements is the voltage level. It has to be kept between the established limits. In order to do that, the distribution network companies should decide the best strategy using the technology within reach. In that case, thinking of the voltage, the transformers are the main tool, especially transformers with tap changer. Based on the real data, we build the models and we run several simulations of them. Once we have the results of the simulations, we analyze them in order to discover potential problems. Then, we modify the settings of the model, especially in the transformer side, to investigate any change in the system that could improve the voltage quality. Another aim of this thesis is to confirm theoretical aspects of the voltage, related to the set point and the dead band. So, with help of the simulation results, we look for relations between the voltage and others parts of the system like the losses or the tap changer operation. Power quality has become major concern to both electric utilities and customers. In many countries, the effects of lack of power quality have been resulting in wastage of several billions of dollars every year. This is due to carelessness of most industries in not upgrading their plants which result in very high cost due to loss of products, loss of production time, clean up and recalibration of the process. The use of complexity and sensitivity of new technologies in electric equipments is one of the major causes of power quality problems such as voltage disturbances on the supply network. Power electronic equipments are more sensitive to voltage disturbances and leads to large growth of voltage disturbances. It is difficult to detect the sources leading to power quality problems. Factors for the causes of most power quality problems are beyond the control of utilities and can never be totally eliminated. Moreover, in this paper, the optimized control scheme for the proposed system is introduced in order to achieve dynamic voltage compensation. In terms of power density, the use of a medium frequency (MF)/HF transformer reduces volume and weight up to 50% and 70%, respectively, compared to previous approaches which employ an additional LFT and/or require an additional winding on the existing 50/60 Hz core. Since the PEs module is employed without a bulky energy storage system such as electrolytic capacitors, its size and mass can be reduced and the reliability also can be increased. The major advantages of the proposed system are as follows.

1) The proposed system has a wide range voltage compensation that can correct both the sags and swells of the grid voltage.
2) The proposed system can be an easy retro-fit solution, without modifying or replacing the existing distribution transformers.
3) The partial power processing capability of the PEs allows for the reduced power rating of the converter and provides the improved entire efficiency for the system.
4) The proposed approach does not need any bulky components such as an LF transformer and/or the huge dc-link electrolytic capacitors in the PE module, resulting in reduced size and mass.
5) Under normal operating conditions, the PEs module operates in bypass mode, processing no power; it processes power only during disturbance events, resulting in higher reliability and efficiency.
6) Under external fault conditions, a bypass switch protects the PEs module from over current.
7) Fast dynamic response is possible.

II. POWER QUALITY PROBLEMS

The electric power network has undergone several modifications from the time of its invention. The modern electric power network has many challenges that should be met in order to deliver qualitative power in a reliable manner. There are many factors both internal and external that affect the quality and quantity of power that is being delivered. This chapter discusses the different power quality problems, their causes and consequences.

A. Interruptions:

It is the failure in the continuity of supply for a period of time. Here the supply signal (voltage or current) may be close to zero. This is defined by IEC (International Electro technical Committee) as "lower than 1% of the declared value" and by the IEEE (IEEE Std. 1159:1995) as "lower than 10%". Based on the time period of the interruption, these are classified into two types. They are,

i) Short Interruption: If the duration for which the interruption occurs is of few mille seconds then it is called as short interruption.

ii) Long Interruptions: If the duration for which the interruption occur is large ranging from few mille seconds to several seconds then it is noticed as long interruption. The voltage signal during this type of interruption is shown in Fig.2.

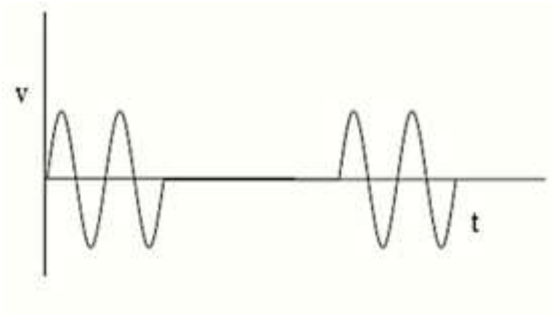

Fig.2 Voltage Signal with Long Interruption

B. Waveform Distortion:

The power system network tries to generate and transmit sinusoidal voltage and current signals. But the sinusoidal nature is not maintained and distortions occur in the signal.

C. Frequency Variations:

The electric power network is designed to operate at a specified value (50 Hz) of frequency. The frequency of the framework is identified with the rotational rate of the generators in the system. The frequency variations are caused if there is any imbalance in the supply and demand. Large variations in the frequency are caused due to the failure of a generator or sudden switching of loads.

D. Transients:

The transients are the momentary changes in voltage and current signals in the power system over a short period of time. These transients are categorized into two types impulsive, oscillatory. The impulsive transients are unidirectional whereas the oscillatory transients have swings with rapid change of polarity.

E.Voltage Sag:

The voltage sag is defined as the dip in the voltage level by 10% to 90% for a period of half cycle or more. The voltage sag as shown in Fig. 3.

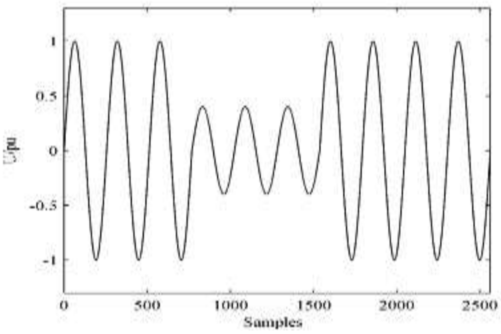

Fig.3 Voltage Sag

F. Voltage Swell:

Voltage swell is defined as the rise in the voltage beyond the normal value by 10% to 80% for a period of half cycle or more. The voltage swell as shown in Fig.4.

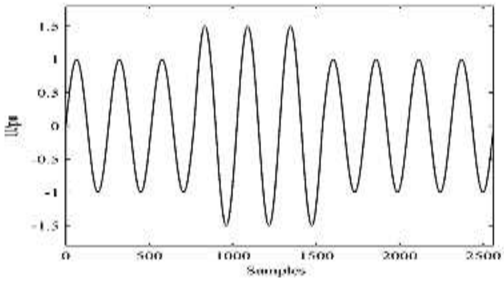

Fig.4 Voltage Swell

G. Voltage Unbalance:

The unbalance in the voltage is defined as the situation where the magnitudes and phase angles between the voltage signals of different phases are not equal.

H. Voltage Fluctuation:

These are a series of a random voltage changes that exist within the specified voltage ranges. Fig.5 shows the voltage fluctuations that occur in a power system.

Fig.5 Voltage Fluctuation

III. SYSTEM MODELING

A fundamental component in providing reliable electricity to the end-user is the step-down distribution transformer, as shown in Fig. 6. This distribution transformer operates at line frequency (LF) (50/60 Hz) to step down from medium voltage (MV) to low voltage (LV). Even if the conventional distribution transformer is relatively inexpensive, highly efficient, and reliable, it is not guaranteed to protect loads from undesirable events such as voltage sags and swells.

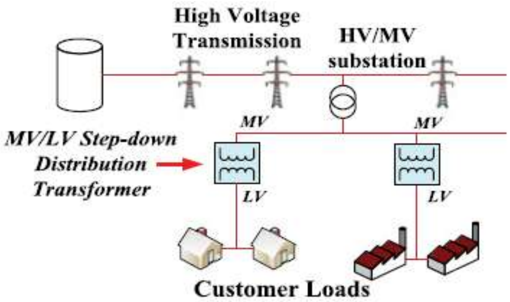

Fig:6. Conventional step-down distribution transformer in the distribution grid network.

Voltage sags and swells have become one of the most critical power quality issues faced by many industrial consumers in power distribution systems. As the complexity of the electronics equipment used in the industrial applications grows, the customer loads are becoming more vulnerable to voltage disturbances such as sags and swells. Voltage sags/swells cost hundreds of millions of dollars every year in the United States.

The voltage sags and swells result in significant economic losses in a wide range of industries, including financial services, health care, and process manufacturing.

Consequently, it is suggested to include voltage compensation functionality in the conventional MV/LV step-down distribution transformer in Fig. 6. Voltage sags and swells can be described by two essential characteristics: magnitude and duration. The survey of power quality presents that voltage sags with 40–50% of the nominal value and with duration from 2 to 30 cycles occurred in about 92% of all power system events. However, these voltage compensators require an extra bulky LF transformer (LFT) and/or huge energy storage capacitors causing challenges in integrating them with the existing distribution transformer.

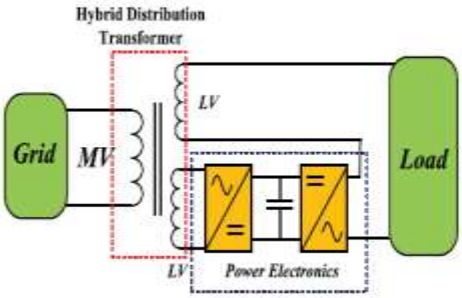

Fig:7. Configuration of the hybrid distribution transformer.

A similar concept called the hybrid distribution transformer, shown in Fig. 7, has been previously introduced to regulate output voltage by utilizing fractional rated PEs. Also, a hybrid transformer utilizing matrix converter was proposed. The concept was proposed more than a decade ago. However, this system requires a dc-link energy storage system such as the electrolytic capacitor. Furthermore, this system requires an additional winding to be wound on the core of the existing bulky LF distribution transformer. Consequently, this approach adds economical and mechanical constraints for distribution network application because it is required to modify or replace the entire bulky size existing distribution transformer in order to provide voltage compensation functionality in the distribution grid network.

This project introduces a voltage sag and swell compensator that can be easily integrated to the standard dry-type existing distribution transformer without replacing or modifying it. A conceptual schematic of the proposed distribution transformer is shown in Fig. 8. The proposed system is composed of the existing LFT connected to a PEs module that is auto connected on the secondary side in order to compensate for voltage sags and swells. This auto connection enables a shunt input and series-output compensator without any capacitive energy storage. Hence the proposed system is structurally and functionally different from the conventional series compensator such as DVR. The proposed system utilizes the input voltage *V*in in order to generate the compensating voltage *Vc*. This is rather considered as a tap changer transformer which regulates the load voltage by varying the turns ratio of the transformer utilizing source voltage instead of using energy storage system in the DVR.

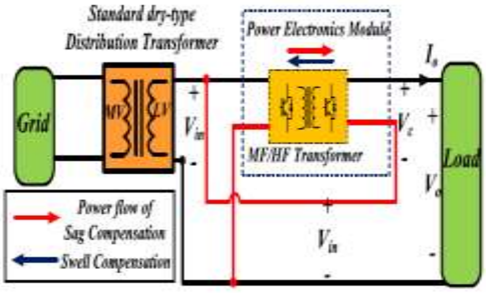

Fig:8. Conceptual scheme of the proposed distribution transformer with power electronics module.

Due to its structure, the partial power processing capability in the PEs module allows for a reduced rating in the proposed system. Also, the efficiency can be maximized during the bypass mode in the whole system. The PEs module generates a compensating voltage, which is vector-added to the grid voltage in order to regulate the output voltage supplied to the load.

The detailed schematic diagram of the PE module for the proposed distribution transformer is shown in Fig. 9. The PE module consists of four single-phase H-bridge converters, MF/HF transformer, output filter, static bypass switches, and DSP controller as seen in Fig. 9. Two H-bridge converters (*M*2, *M*3) connected directly to the MF/HF transformer operate at a high switching frequency while the other two converters (*M*1, *M*4) operate at LF. An MF transformer can be employed for relatively higher power applications, while an HF transformer may be preferred for lower power residential-type applications.

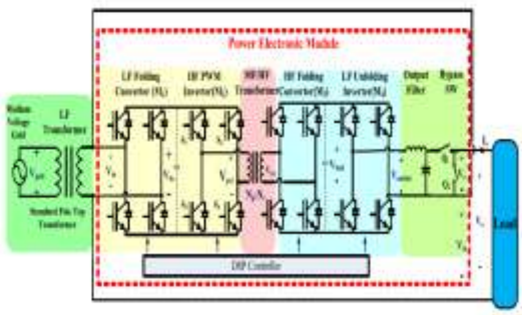

Fig:9. Detailed power electronics module in the proposed distribution transformer.

The PE module operates in voltage compensation mode or by pass mode. During bypass mode, the grid-side voltage (*V*in) is directly connected to the load-side by closing a bypass switch*Q*2 and opening a bypass switch *Q*1. When voltage sags and swells occur on the grid-side, the bypass switch *Q*2 is opened and *Q*1 is closed so that the PWM switches are activated to supply the required compensating voltage (*Vc*). Since the bypass switch is activated by a voltage magnitude detection algorithm, the operating bypass mode and compensation mode are determined by voltage magnitude changes in the grid. Moreover, turning ON switches *S*3 *M*4 and *S*4 *M*4 in the LF unfolding inverter (*M*4) can be utilized in place of having bypass switches *Q*1 and *Q*2 during normal condition. This reduces switching losses in the entire system by avoiding operating static bypass switches *Q*1 and *Q*2. The secondary side of the *MF/HF* transformer also has a similar *HF* folding converter *M3* followed by the *LF* unfolding inverter as shown in Fig.9.

IV. SIMULATION RESULTS

The detailed schematic diagram of the PE module for the proposed distribution transformer is shown in figure. The PE module consists of four single-phase H-bridge converters, MF/HF transformer, output filter, static bypass switches, and DSP controller as seen in Figure. Two H-bridge converters ($M2$, $M3$) connected directly to the MF/HF transformer operate at a high switching frequency while the other two converters ($M1$, $M4$) operate at LF. An MF transformer can be employed for relatively higher power applications, while an HF transformer may be preferred for lower power residential-type applications.

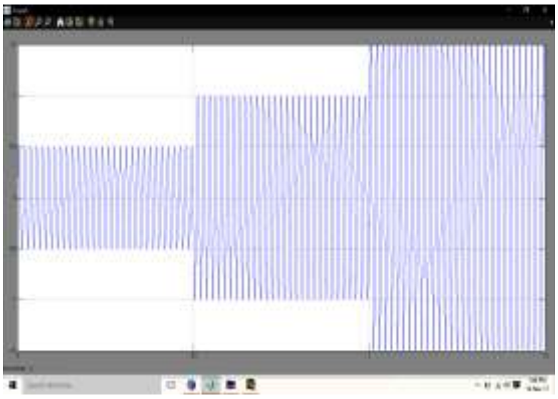

Fig:10(a)

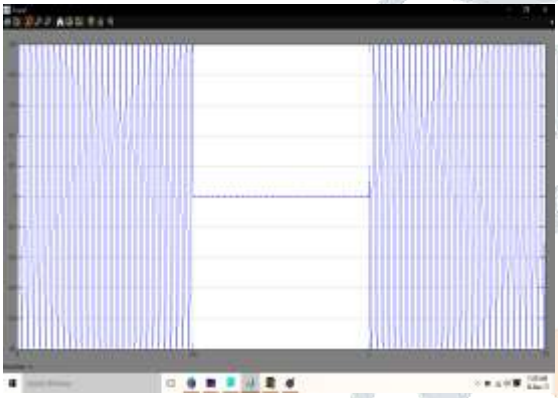

Fig:10(b)

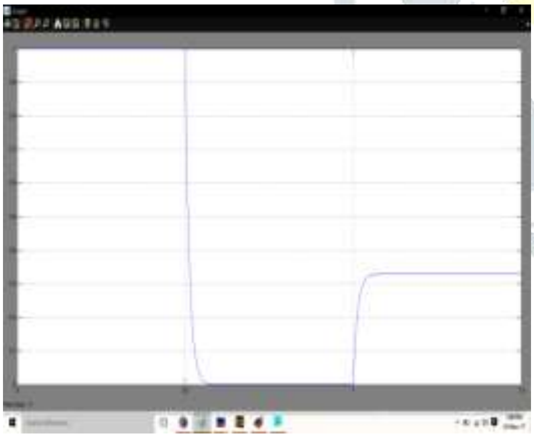

Fig:10(c)

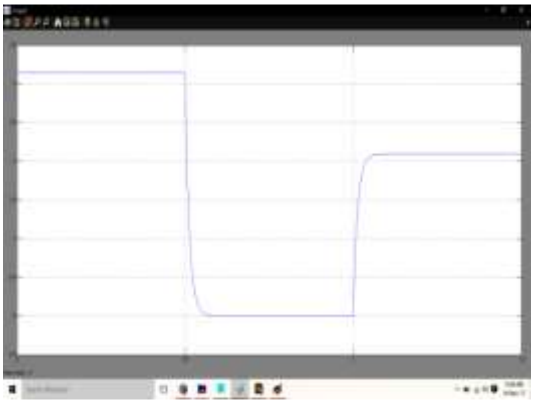

Fig:10(d)

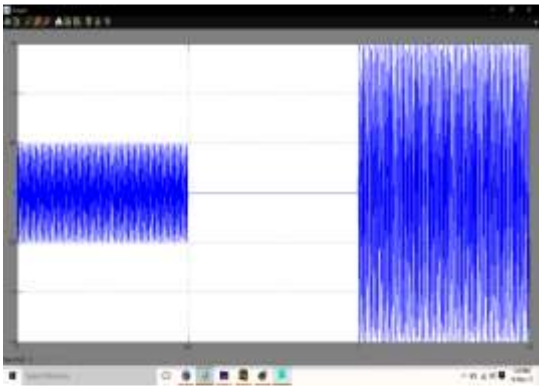

Fig:10(e)

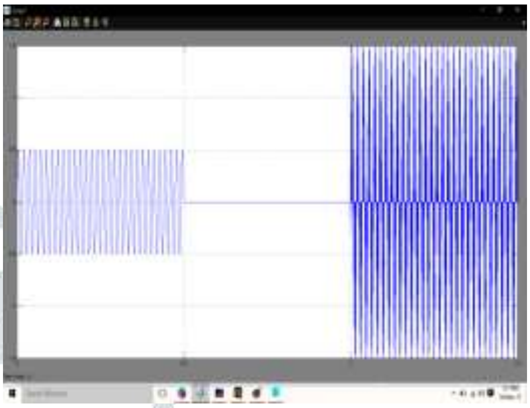

Fig:10(f)

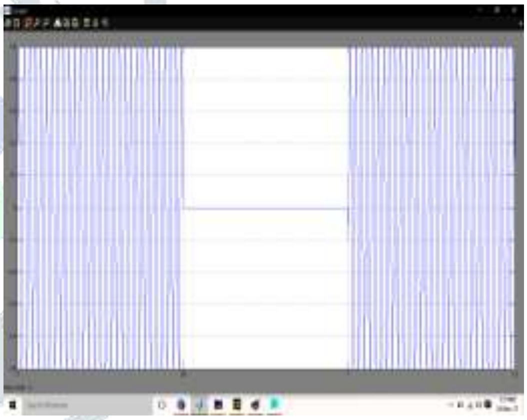

Fig:10(g)

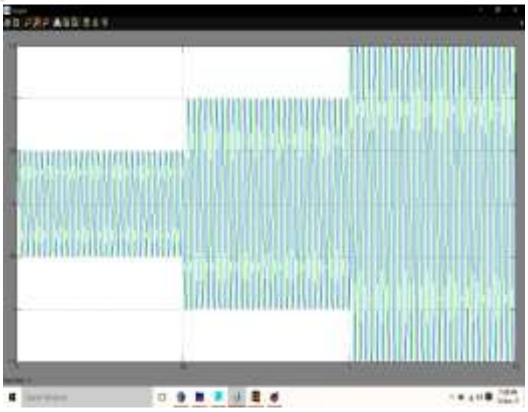

Fig:10(h)

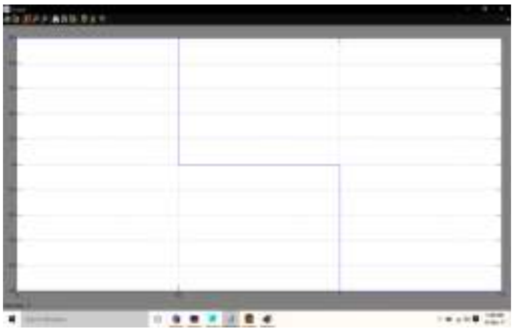

Fig:10(i)

Fig:10. Ideal operation for phase shift modulation in the proposed control scheme at 1:1 turns ratio: (a) Source voltage *v*in with 50% sag, normal and 50% swell, (b) compensating reference signal *vc*,ref , (c) duty *D*ff , (d) phase shift angle Φ, (e) primary voltage of the MF/HF transformer *v*pri , (f) unfolded voltage *V*unfold , (g) compensating voltage *Vc* , (h) normalized source voltage V^{β}in , 90° phase delay normalized source voltage V^{α}in , and normalized input voltage magnitude *Vm* , and (i) voltage detection signal *S*ref .

The control scheme for the proposed system is introduced in this section. Fig. 10 shows operation waveform of the proposed control scheme based on the control block diagram. The control block diagram includes a load voltage control block and a compensating voltage reference generation block. When the voltage sag/swell occurs, the compensating voltage reference generation block generates duty ratio *D*ff, based on the amount of voltage sag/swell. Also, the load voltage control block generates duty ratio *D*fb, to regulate the desired load voltage. The compensating voltage reference *Vc*, ref shown in Fig. 10(b) for voltage sag or swell is obtained by subtracting the normalized grid voltage signal *V*in,norm from the normalized ac reference signal *Vo*,ac ref the unity magnitude sinusoidal signal generated by the fundamental frequency detection methods. The angle of phase delay (φ) in the control scheme is obtained by a conversion of the duty ratio radian after adding *D*ff and *D*fb as seen in Fig. 10(d). Then, this phase angle delay φ is adjusted in order to generate compensating voltage *Vc* as shown in Fig. 10(e)–(g). In the compensating voltage sags and swells detection block, a voltage magnitude of the input voltage *Vm* is obtained as shown in Fig. 10(h) A voltage detection signal *S*ref for voltage sag or swell is determined by subtracting *Vm* signal from normalized dc reference voltage signal *Vo*, dc ref as shown in Fig. 10(i). As shown in Fig. 10(e), the primary voltage *V*pri is generated HF based on the obtained phase shift angle φ from the control scheme. Assuming that a 1:1 MF/HF transformer is selected, the compensating voltage for 50% sag condition can be generated by superimposing the maximum phase angle φ which is $\boldsymbol{\pi}$ in rad on the 50% sagged LF pulsating voltage as shown in Fig. 10(e)–(g). For the 50% swell condition, the primary voltage has $2\pi/3$ in rad phase delay superimposed on an LF swelled pulsating voltage as shown in Fig. 10(e). The 180° out-of-phase compensating voltage *Vc* is provided by filtering out HF components from unfolded voltage as shown in Fig. 10(f) and (g).

V. CONCLUSION

In this project, a series voltage regulator for the distribution transformer to compensate voltage sags/swells along with its control scheme was introduced. The proposed approach was easily integrated into existing conventional distribution transformers in order to provide sag or swell compensation capability for a distribution grid system. Experimental results demonstrated voltage sag and swell compensation without a dc-link and associated electrolytic capacitors. Due to partial power processing, the PE module had a lower voltage rating and, for the same reason, The MF/HF transformer had a lower VA rating than the load. Therefore, the proposed system is a possible retro-fit solution for existing distribution transformers to improve power quality in the future grid**,** especially in the face of the proliferation of renewable and distributed generation**.**

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