MITIGATING ELECTRICAL DISTURBANCES WITH HYBRID DISTRIBUTION TRANSFORMER

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ABSTRACT

Hybrid transformers (HT) have the advantages of the conventional transformer, the regulatory abilities of power electronic converters, and reduce the impact of the grid. The impacts of the existing grid are voltage sag, voltage swell, harmonic distortion, and voltage unbalanced. The power electronic converter has a controllable advantage such as regulating the voltage and can transfer only a fraction of the power. The aim of the paper is to augment the conventional power distribution transformer with a partially rated power electronic module to enhance flexibility and introduce new features to the distribution transformer. In this paper, the proposed back-to-back converter included an active front rectifier and a modular multilevel converter (MMC) was simulated by MATLAB/Simulink software. The proposed back-to-back converter was used at the primary side of the distribution transformer to compensate for the voltage sag and swell issues. The simulation results were obtained under different conditions such as various supply voltages and various loads. Hence, the proposed system has the ability to regulate the output voltage under various conditions with ±10%.

KEYWORDS

Hybrid transformer, voltage sag, voltage swell, back-to-back converter

1. INTRODUCTION

The most significant problem of power quality in AC power systems is the voltage amplitude [1]. In the industry, some devices are sensitive to voltage variation that leads them to be damaged. Therefore, the peak loss in the industrial field reached more than 55% [2]. The main causes of the voltage fluctuations are the dynamic loads' variations, the effect of the switching, and weather conditions variation disturbing renewable energy resources such as solar and wind [3]. In addition, adding modern loads such as electric vehicles as well as installing more renewable energy resources are reasons to cause power quality issues such as voltage fluctuation. In the industrial field, the power quality issues are poor power factors, high frequency interference, and current harmonics. On the load side, the power quality issues are poor power factor, unbalance voltages, voltage sag/swell, and conducted interference [4].

Voltage sag and swell were the most terrible issues on the power quality, which are challenges for the industrial field in the distribution system. The voltage sag is a voltage reduced between 10% and 90% of the nominal RMS voltage for a period of 0.5 cycles to 1 minute. The causes of the voltage sag are the heavy loads and the faults in the distribution network. Therefore, the consequences of the voltage sag are decreased efficiency and malfunction of modern electronic devices. The voltage swell is a rise of the voltage out of the nominal tolerance at a period of more than 1 cycle which is about less than a few seconds. The causes of the voltage swell are poorly controlled transformer, poorly power source, and turn on/off large loads. Its consequence

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is damaging the delicate devices [5]. Voltage unbalance level is the voltage value or phase angle variation in a three-phase system that does not has an equal difference between the three phases. The causes of voltage unbalance are heavy load in single-phase and unbalance distribution of loads in all single-phase. In addition, the consequence of the voltage unbalance level destroying all three-phase loads. The conventional distribution transformer does not have the capability of handling the power quality problems such as voltage sag/swell and voltage unbalance. In the industrial field, complex power electronics devices are used, and this is the reason that the consumer loads are delicate to the voltage fluctuations. The health care, process industries, and the economic losses are the bad effects of the voltage sag and swell [6-9]. Table 1 illustrates the description, causes, and consequences of other power quality issues such as short interruptions, long interruptions, voltage spike, harmonic distortion, and voltage fluctuation [5].

Table 1: illustrates that the power quality issues, causes, and consequences [5].

Power Quality issues	**Description**	**Causes**	**Consequences**
Short interruptions	The period of the interruption will be from milliseconds to one or two seconds.	Isolation damage.	Activate protection equipment and cutoff sensitive devices.
Long interruptions	The period of the interruption will be more than one to two seconds.	A collapse in the power system network, human errors, and damage of protection equipment.	Cutoff all devices.
Voltage spike	It is a rapid change in the voltage for a small period approximately from microsecond to milliseconds.	Stoppage of large loads, switching lines, and the capacitor of mitigation the power factor.	Damage electronic devices, damage the insulation material, and electromagnetic interference.
Harmonic distortion	The non-sinusoidal waveform as current and voltage match to the sum of varying sinewaves and with various phase angle and magnitude values, consuming frequency that is numerous of powersystem frequency.	Nonlinear loads	Decrease the efficiency, overheating all the cables, and electromagnetic interference.
Voltage fluctuation	It is a voltage amplitude variation.	Load variations and repeated turn on/off motors.	Fluttering of lamp and monitor.

The integration of renewable energy resources and the grid, the growth of switch-mode power converters, industrial and domestic nonlinear, and charging station for the electric vehicle have a terrible impact on the power quality of the distribution network [10]. The conventional distribution transformer cannot deal with the power quality issues such as voltage sag/swell and voltage unbalance.

The increased penetration of electric vehicle charging systems and distributed generation will create power quality issues in the low-voltage distribution grid (LVDG) like voltage variation in the grid, voltage sag/swell, harmonic distortion, and weak power factor. The on-load tap changers or dynamic voltage restorers with distribution transformers are one of the solutions that can be used to mitigate the power quality issues in the LVDG [11]. On-load tap changers are widely integrated with the distribution transformer in order to compensate for voltage fluctuation. However, the on-load tap changers have main drawbacks such as a strict range of output compensation, bad dynamics of voltage regulation, and stepwise alteration [12-14]. Dynamic voltage restorer (DVR) is a power electronic equipment used to protect the loads that are susceptible to voltage troubles (rapid voltage sags/swell) at the point of common coupling (PCC) [15], [16]. The main operation of DVR is inserting a voltage with a demanding phase, magnitude, and frequency. In addition, the DVR is connected to the distribution feeder in series in order to keep the required waveform and amplitude for the voltage of the load even if the voltage is disturbed [17]. Dynamic sag corrector (DySC) is another technique used to compensate for voltage fluctuation and also can be combined with the distribution transformer [18], [19]. The DySC is established on the power electronics components which use an AC-AC converter with pulse width modulation (PWM) to assure perfect dynamic features. Ride-through voltage compensators and Dynamic sag correctors (DySC) can be used to solve the issues of the power quality on the distribution line customer by supplying voltage sag compensation with a decreased cost [20-21]. However, they can be used to mitigate voltage sag only [18-22]. The fast response advanced system, voltage phase angle control and sag mitigation, harmonic filtering, and reactive power compensation are requirements to achieve voltage regulation in terms of dynamics and accuracy.

Solid-state transformer (SST) is based on power electronic converters of a three-phase line. SST is one of the techniques to solve power quality issues. However, SST has some drawbacks such as lower efficiency, a higher cost compared to traditional transformer [23]. The optimistic technology to improve the power quality of the grid is the hybrid transformer. Hybrid transformer is consisting of a conventional transformer and a partially rated power electronic converter. The advantages of the hybrid transformer are lower complicated, lower price, and keep the efficiency high compared to the SST [24]. Therefore, the hybrid transformer is a hopeful solution to enhance the power quality of the grid. The power electronic converter is capable of compensating active and reactive power, regulating the voltage, balancing the currents of the load, and filtering harmonics [25].

The hybrid transformer's (HTs) classification is illustrated in Figure 1 [26]. The first category of HTs is according to the method of injecting the electrical energy through the power converter which can be a series technique or parallel technique. The second category is according to utilizing the power converter with and without DC energy storage. Systems without DC energy storage can be utilized with series inserting electrical energy systems. These systems can be utilized as direct or indirect matrix converters [27] or AC - AC choppers [28]. On the other hand, systems with DC energy storage are utilized with shunt inserting electrical energy systems. Such systems are able to regulate a large voltage sag. However, the cost of these systems is expensive, and its size is large. In addition, the DC energy storage has low reliability [29]. The last category is according to utilizing the galvanic separation between the input of the converter and/or the terminals of the load. The power converter can get the electrical energy from an extra transformer winding or straight from the terminal of the HT load. Furthermore, the power converter's output voltage can be combined straight with another winding voltage or through an extra isolated transformer [30].

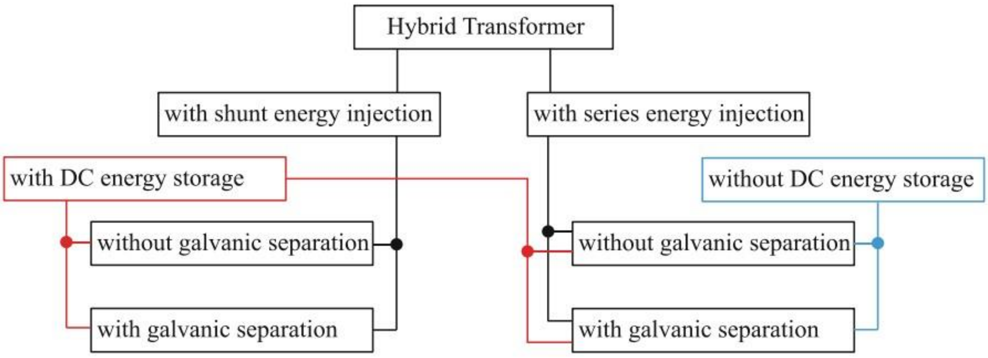

Figure 1. Hybrid distribution transformer classification [26].

There are different approaches to integrating the converter with the distribution transformer to build the HT as shown in Figure 2. In the first approach, a current can be injected either on the primary or secondary sides of the transformer by utilizing a shunt connection with a power electronic converter as illustrated in Figure 2 (A). In the second approach, a voltage can be injected either on the primary or secondary sides of the transformer by utilizing a series connection with a power electronic converter as shown in Figure 2 (B). The third approach, Figure 2 (C) is the combination of series and shunt connection of the power converter. The conventional distributed transformer can be connected with a power electronic converter by using a direct inserting transformer or through the auxiliary winding. The first approach can correct the power factor, insert reactive current and eliminate the harmonics. The second approach can compensate for the voltage of the load by injecting a reactive voltage. The first and the second approaches do not flow active power through the power converter. This disadvantage does not exist on the third approach [31].

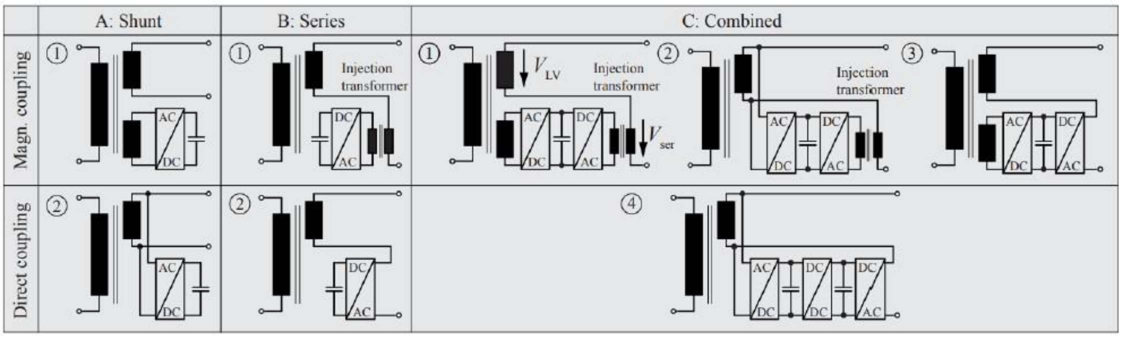

Figure 2. Different HT approaches Shunt-connected converters (A), series-connected converters (B), and a combination of series and shunt-connected converters (C) [32].

In General, there are two methods of the structures of the hybrid transformer to connect the power electronic converter. The first method is to integrate the power electronic converter into the high voltage side of the distribution transformer (DT) which has the benefit of low currents and no converter neutral wire. However, it consumes a high voltage power electronic transistor. The second method was to integrate the power electronic converter into the secondary side of the DT which has low voltage and high current. In the selected HT construction, the power electronic converter is located on the high-voltage side of the DT [33]. The main object of this paper was to compensate for the output voltage under sag and swell issues by HT.

This paper presents: 1) the circuit configuration of the proposed back-to-back converter in the primary side of the DT to compensate for the output voltage and 2) simulating the proposed HT under different conditions as various supply voltages and various loads. The AC grid provides the system with direct 90% of the supply to the load side and 10% of the AC grid will provide the proposed back-to-back converter at the proposed system. The proposed HT is based on MMC to compensate for the output voltage with a range of ±10%.

The rest of the paper is organized as follows: section 2 represents the circuit configuration converter and the challenges of MMC circuit. Subsection 2.1 represent the design of the proposed back-to-back converter. Section 3 represents the control of the proposed converter. Section 4 represents the simulation results under different conditions. Section 5 is the conclusion of the paper.

2. CIRCUIT CONFIGURATION CONVERTER

The proposed back-to-back converter included an active front rectifier and a modular multilevel converter (MMC) inverter was used to compensate for the voltage sag and swell issues. The proposed converter was integrated at the primary side of the distribution transformer. The proposed back-to-back converter used an active front rectifier to reduce the volume and cost of the proposed converter. The purpose of the rectifier is to regulate the DC voltage on the DC link. The MMC is one of the multi-cell converter family which is new progress and has the capability to work in medium voltage (2.3–13.8 kV) to high voltage (33–400 kV) and power rating of 0.226-1000MW [34]. The MMC is useable in high-power conversion because of its lower output THD, high voltage scalability, and higher modularity [34]. The circuit configuration is illustrated in Figure 3.

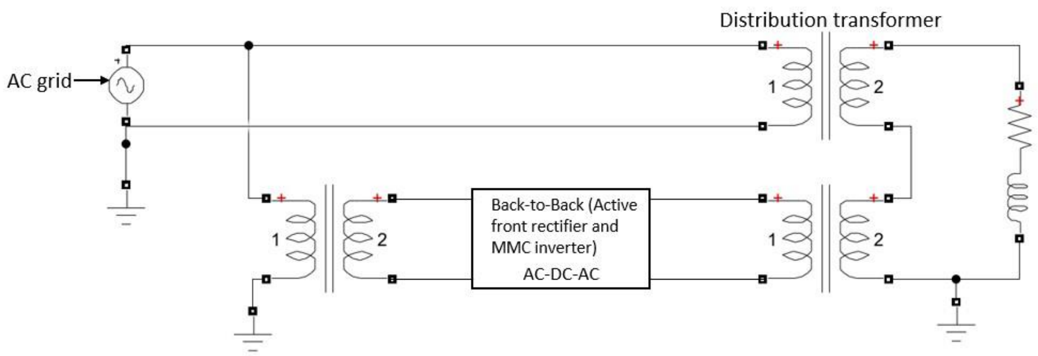

Figure 3. The proposed back-back converter in the primary side of the DT.

The MMC is one of the multi-cell converter family which is new progress and has the ability to work in medium voltage to high voltage and power rating of 0.226-1000MW. The purpose of adding more submodules in each arm is to increase the voltage and power capacity of the MMC. The MMC is used in high-power applications because of its lower output THD, high voltage scalability, and higher modularity [33]. The control and operation of the MMC have technical challenges as follows:

1) Submodule Capacitor Voltage Control: The voltage of the submodule capacitor should be fixed at the reference voltage value. The circulating current problem was due to the voltage unbalance between the arms. The direction of the arm current and capacitor voltage is the factor that affects the voltage balance among the submodules.

2) Submodule Capacitor Voltage Ripple: The voltage ripple of the submodule capacitor is due to the interaction between the arm currents and voltage.
3) Circulating Currents: The voltage difference between the arms in each leg cause circulating currents. The peak and RMS value of the arm current grew by the circulating current leading to a rise in the converter power losses and the ripple in submodule capacitor voltage.

The three-phase MMC configuration is shown in Figure 4. The MMC leg is divided to be two arms (upper arm and low arm). The arm is consisting of submodules and a series inductor to limit the current due to the voltage difference between the arms. The core advantages of MMC are able to scale the voltage and the power rating and the output voltage has very low total harmonic distortion (THD). In addition, the MMC has the ability to produce the output voltage waveform with a very large number of voltage levels. Also, the MMC can operate with a low switching frequency [35].

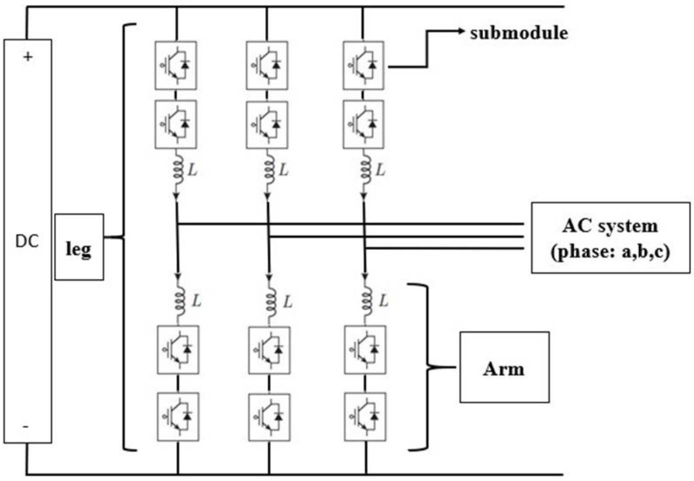

Figure 4. Circuit configuration of the MMC.

A submodule (SM) configuration is a combination of low-voltage IGBT devices and capacitors. The half-bridge (HB) submodule, full-bridge (FB) submodule, flying capacitor (FC) submodule, cascaded half-bridge (CH) submodule, and double clamp (CD) submodule are used as submodule configurations in MMC. The structure of the HB is two semiconductor devices and a floating capacitor. The HB is a simple design and control as in standard process one of the devices will be ON. The low power losses and high efficiency are the advantages of the halfbridge submodule. The positive levels are the results of the output voltage of the half-bridge submodule.

2.1. Design the Proposed Converter

The proposed converter is a combination of the rectifier and the MMC. The design of the MMC will be based on the capacitance value of the submodule, inductor size, and the number of the submodule. The number of submodules is determined by dividing the DC-link voltage by the desired voltage of the submodule capacitor. The voltage and current ripples in the converter will be limited depending on the suitable SM capacitor size. The SM capacitor is depending on maximum capacitor voltage, voltage ripple, current ripple, and SM voltage capability. Hence, the SM capacitor C should be sized based on the amount of voltage excess, $V_{\max p.u}$ as follows [36]:

$$C \geq \frac{\sqrt{2NI_{ac}}}{\omega V_{\max p.u} V_{dc}} f_{max}(m, \varphi) \qquad (1)$$

where I_{ac} is the magnitude of the RMS value of the AC side current, N is the number of SMs in an arm, ω is the fundamental angular frequency, V_{dc} is the DC-link voltage, m is the modulation index, φ is the power factor angle and $f_{max}(m, \varphi)$ is the voltage excess function [36].

Suppressing the second-order harmonic component of circulating current among the arm and limiting fault current in the event of a DC short circuit fault are the main functions of arm inductance. Equation (2) shows the arm inductance calculation [36].

$$L_{arm} = \frac{1}{8\omega^2 C V_c}\left(\frac{P_s}{3I_{2f}} + V_{dc}\right) \qquad (2)$$

where ω is the fundamental angular frequency, C is the capacitor of the SM, V_c is the DC component of the capacitor voltage, P_s is the apparent power, I_{2f} is the peak value of the AC component of the circulating current i_{2f} and V_{dc} is the rated DC bus voltage [36].

The design of the rectifier is based on the capacitance value of the DC-link. The desired capacitance value was calculated by the following equation [37]:

$$C = \frac{V_{dc}}{2R * f_{sw} * \Delta V_{dc}} \qquad (3)$$

ΔV_{dc}: is the voltage ripple, f_{sw} is the switching frequency, R: is the resistive load, and the Vdc: is the DC voltage.

3. Control Proposed Converter

The control of the system was divided into two parts. The first part was to control the active front rectifier which was responsible for regulating the DC-link voltage. The desired voltage of the rectifier was dependent on the supply voltage. There were equations based on the supply voltage for each case (normal supply voltage 11kV, sag supply voltage 10kV, swell supply voltage 12kV) in order to determine the desired DC-link voltage. The equations will be illustrated as follow:

$$V_{DC} = \frac{3}{2} * \left(\frac{11000}{\sqrt{3}} - V_s\right) * \sqrt{2} + \left(\frac{3}{2}\right) * \frac{1100 * \sqrt{2}}{\sqrt{3}}; (sag\ case) \qquad (4)$$

$$V_{DC} = -\frac{3}{2} * \left(V_s - \frac{11000}{\sqrt{3}}\right) * \sqrt{2} + \left(\frac{3}{2}\right) * \frac{1100 * \sqrt{2}}{\sqrt{3}}; (swell\ case) \quad (5)$$

$$V_{DC} = \left(\frac{3}{2}\right) * \frac{1100 * \sqrt{2}}{\sqrt{3}}; (normal\ case) \quad (6)$$

where the ratio between the desired DC-link voltage and the desired output AC voltage was selected to be 3/2, V_{DC} was the DC-link voltage, V_S was the actual supply voltage (RMS). In normal conditions, the converter feeds the system with 10% of the supply power and 90% direct from the grid to the load side through the distribution transformer as illustrated in equation (6). In the sag condition, the supply voltage will decrease under the normal voltage, so the converter was responsible for compensating for the required voltage as illustrated in equation (4). Therefore, a positive term was added to the normal equation. In the swell condition, the supply voltage will increase above the normal voltage, so the converter was able to compensate for the required voltage as illustrated in equation (5). Hence, a negative term was added to the normal equation to regulate the output voltage of the DC-link.

The second part was to control the MMC which was responsible for balancing the voltage through the submodule and regulating the AC output voltage. The control of the MMC was based on the d-q reference. The control was consisting of two control loops. The outer loop was voltage control while the inner loop was current control. The peak desired output voltage was 340 V and the control diagram will be shown in Figure 5. There were different pulse width modulation (PWM) techniques used to balance the DC voltage of submodules in each arm. The Level Shifted PWM and Phase Shifted PWM are types of multi-carrier PWM. Phase Disposition (PD-PWM), Phase Opposition Disposition (POD-PWM), and Alternative Phase Opposition Disposition (APOD-PWM) are types of level-shifted (LS-PWM). The proposed technique was Phase Disposition (PD-PWM) because of its higher capacitor voltage selfbalancing capability and less harmonic distortion for the output voltage [38,39]. There are two submodules per arm. If the current in the arm (upper or lower) is positive and the submodule of the arm is ON, the capacitors will be charged. If the current in the arm (upper or lower) was negative and the submodule is ON, the capacitor of the submodule will be discharged. If the submodule was off, the capacitor voltage will remain constant. In order to balance the voltage of the submodule, for each period of the PD-PWM, the submodule voltages of each arm will be sorted in descending order [39]. The required number of working submodules was illustrated in equation (7).

$$n_{upper} + n_{Lower} = 2 \quad (7)$$

Where n_{upper} is the upper arm and n_{Lower} is the lower arm.
Hence, the voltage of each submodule should be regulated to ($V_{DC}/2$). The required number of the working submodules in each arm is determined by three voltage levels at the AC side of phase (j) and midpoint (O) as follows [39]:

1)Voltage level 1;

$$V_{tjo} = \frac{V_{DC}}{2} \quad (8)$$

All the submodules of the upper are ON and all the submodules of the lower are OFF.

2)Voltage level 2;

$$V_{tjo} = 0 \tag{9}$$

There is one submodule of each arm (upper and lower) are ON.

3)Voltage level 3;

$$V_{tjo} = -\frac{V_{DC}}{2} \tag{10}$$

All the submodules of the upper arm are OFF and all the submodules of the lower arm are ON.

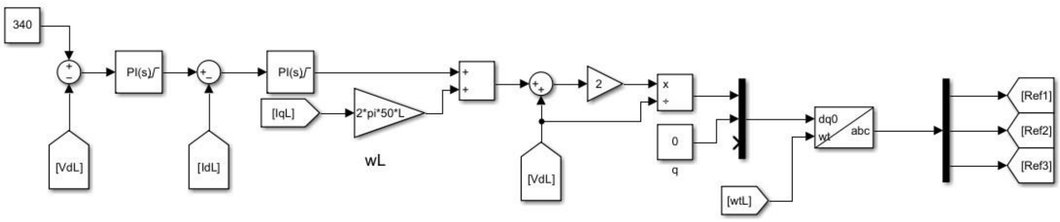

Figure 5. The proposed control of the MMC.

4. SIMULATION

The first simulation part was divided into three cases (normal supply voltage, sag supply voltage, and swell supply voltage). Table 2 illustrates the values of the parameters of the proposed converter. The results of the simulation are illustrated in Figure 6&7. As shown in Figure 4&5, the normal case was simulated during the period (0-1) second and the supply voltage was 11kV. The calculated DC-link voltage was 1350V according to equation (6). The simulated value of the DC-link voltage was around 1350V which was typical of the calculated value. The output voltage of the load side was 340 Vpeak (240 Vrms) as required. The next case was the sag voltage condition which was simulated during the period (1 - 2.2) seconds and the supply voltage was 10 kV. It is noticed that during the transition from the normal case to the sage case, the output voltage dropped below 340 Vpeak for a very short period. The simulated value of the DC-link voltage was about 2570 V which was similar to the calculated value according to equation (4). The output voltage of the load side was regulated to be 340 Vpeak (240 Vrms). The final case was the swell voltage condition which was simulated until the end of the period and the voltage supply was 12 kV. Also, during the transition from sag case to swell case, the output voltage was above the desired voltage for a very short period. The calculated DC-link voltage was 122 V according to equation (5) which was approximately similar to the simulated value. The output voltage was compensated to reach 340 Vpeak (240 Vrms). Overall, the results showed that the proposed hybrid distribution transformer has the ability to compensate for the output voltage under various conditions with ±10%.

Table 2. The values of the parameters in the proposed converter.

Parameters	**Values**
Voltage supply	11kV
Submodule Capacitance	1.9mF
Arm inductance	0.01mH
Submodule Voltage	1000V
DC-link capacitance	5000μF
Load resistor	100Ω
Load inductance	30 mH

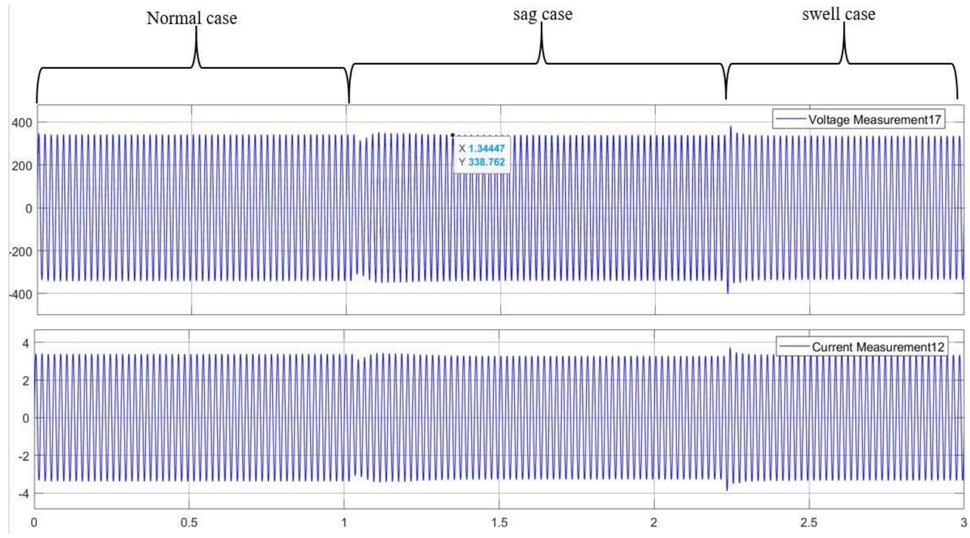

Figure 6. The voltage and current waveform in different conditions of the proposed converter.

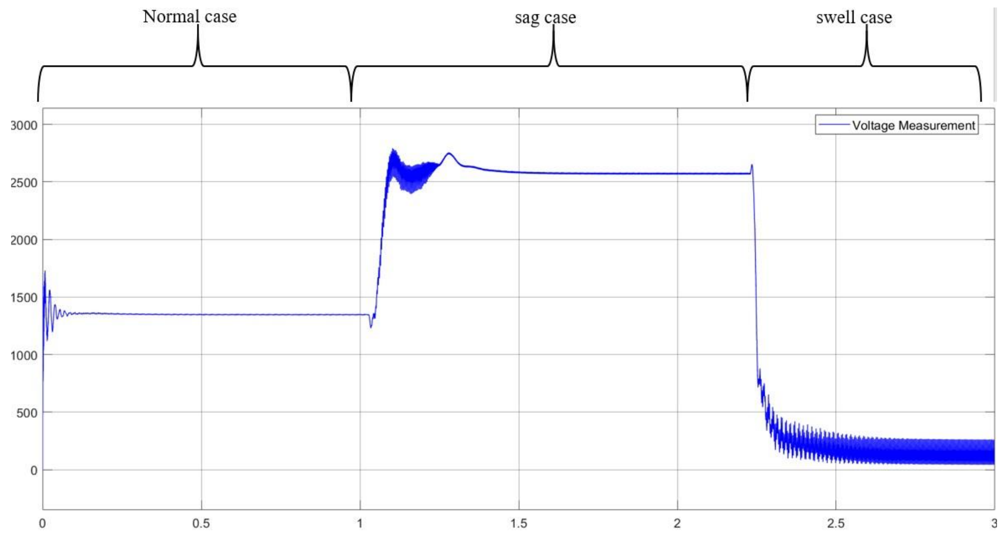

Figure 7. The DC-link of the proposed converter in different conditions.

The second simulation part was unbalanced phase voltage which change one of the load resistors to be different than the other phases. Therefore, the load resistor of phase A was changed to 50 Ω while the resistors of the other phases remain to be 100Ω. As shown in Figure 8, the output voltage of phase A was regulated to be 340 Vpeak (240 Vrms). The output voltage of the load side of the three phases were remain at 340 Vpeak (240 Vrms). Therefore, the proposed hybrid transformer can compensate for the output voltage under unbalanced phase voltage.

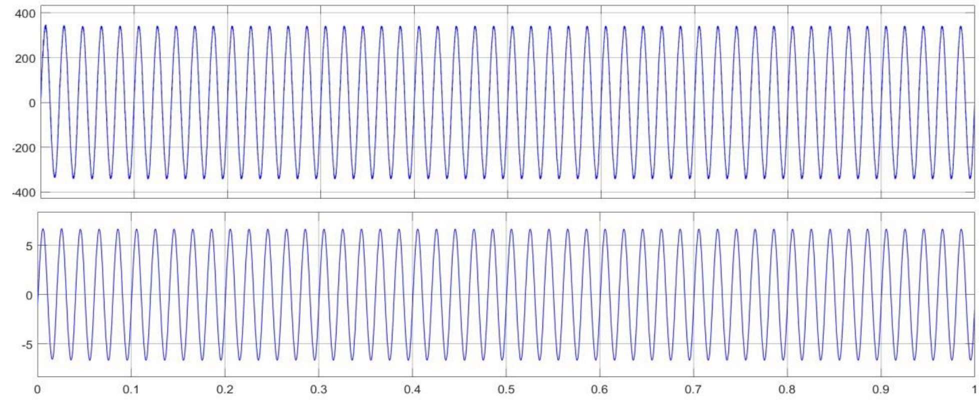

Figure 8. The output voltage and current waveform of phase A.

The third simulation was to change the load side to represent the sag condition. The resistors of the load will be decreased from 100Ω to 50Ω. The output voltage and current waveform of the simulation were illustrated in Figure 9. The result observed that the proposed HT can compensate for the output voltage to be 340 Vpeak (240 Vrms) as required. However, the output current increased according to Ohm's low.

Then, the simulation module was to change the load side to represent the swell condition. The resistors of the load will be increased to 150Ω. The output voltage and current waveform of the simulation were illustrated in Figure 10. The result showed that the output voltage of the load side was regulated to be 340 Vpeak (240 Vrms) as required. However, the output current decreased according to Ohm's low.

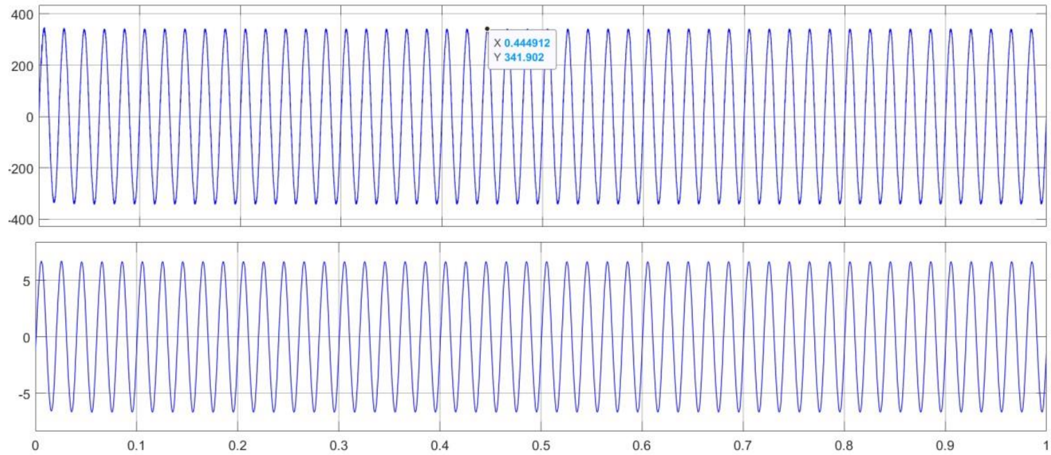

Figure 9. The output voltage and current waveform of the load resistor of 50 Ω.

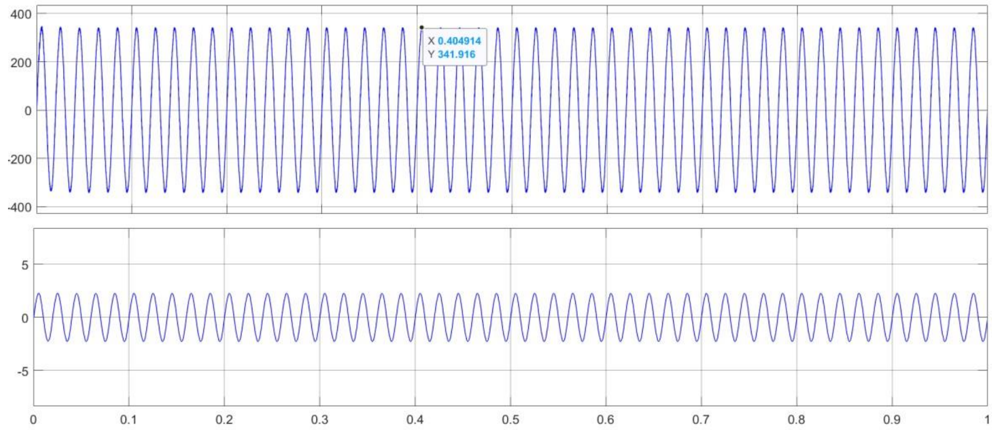

Figure 10. The output voltage and current waveform of the load resistor of 150 Ω.

5. CONCLUSIONS

In this paper, the proposed hybrid transformer is composed of a back-to-back converter which is shunt-connected with the grid through an additional transformer. The proposed back-to-back converter is integrated at the primary side of the distribution transformer. The proposed converter was consisting of an active front rectifier and an MMC inverter. The hybrid transformer is one of the most efficient techniques for solving power quality issues. The proposed hybrid distribution transformer was 90% of the supply power to provide the load directly through the distribution transformer and 10% of the supply power to feed the proposed converter. The proposed HT was simulated under three cases (normal voltage, sag voltage, swell voltage). The results verified that the proposed HT has the ability to compensate for the output voltage of the load side with ±10%. In addition, the proposed HT was simulated under unbalance phase voltage. The results showed that the output voltages of the three phases were similar and reached the required voltage. Finally, the HT was simulated under various load resistors to represent the sag and swell conditions. Overall, the results showed that the proposed HT has the capability of solving power quality issues such as voltage sag and swell conditions. The future work for the system will be studying and investigating the power losses of the switching components and the efficiency of the hybrid distribution transformer. The main scope of future work will be improving the overall efficiency of the system.

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