Electrical Distribution System with High power quality Based on Power Electronic Transformer

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Abstract - *Power Electronic Transformer became more interested in recent years as an alternative to the conventional transformer. Although its behavior is identical to the conventional transformer, power electronic transformer is smaller in size and provides capability for controlling and enhancing the power quality of electrical systems. In this paper, a new configuration of power electronic transformer is considered and examined to perform identical behavior of traditional transformer in electrical distribution system. The proposed topology of this transformer consists of three stages these are; input stage, isolation stage and output stage. The input stage employs three-phase Vienna rectifier for rectifying the AC voltage source and with proper control it keeps input power factor near unity with low harmonic distortion of input currents. Configuring of isolation stage achieved by using single phase inverter connecting to the input of high frequency transformer which its output connected to a single phase uncontrolled rectifier. Three-phase 5-level diode-clamped inverter is utilized as an output stage. Performance of the proposed structure is verified by simulation which indicates high quality results from power utility and harmonic distortion points of view.*

Key Words: PET, power quality, PF improvement, Vienna rectifier and Diode clamped inverter.

1. INTRODUCTION

Transformers represent the backbone of electrical power systems. They used for stepping up or stepping down the voltages in transmission and distribution of electrical power. They are also important in power electronic circuits. Many functions can be achieved through transformers like isolation, noise decoupling or phase shifting [1]. Transformers are bulky, heavy and most expensive parts in electric power systems [2]. Two factors affects on choosing the size of transformers, these are, the core material magnetic properties and maximum allowable temperature of the core and winding temperature rise. For achieving reasonable reduction in transformer size, higher operating frequency is considered for allowing higher utilization of the steel magnetic core [2]. Beside it is bulky and heavy, traditional transformer having some other disadvantages, like sensitive to harmonics, voltage drop under load, poor power factor or power quality under heavy inductive loads [3].

Recent advances in power electronic devices have led to a number of modern power converter topologies, these topologies support for introduce power electronic transformer PET. PET performs the major functions of traditional transformer as well as regulate voltage instantaneously, and improving power factor [4]. The main feature of PET is the utilization of high frequency voltage transformation. Therefore, in order to achieve the main function of conventional power transformer, power electronic converters are connected to the primary and secondary of high frequency transformer. The structure of PET consists of three main stages, these are: input stage, isolation stage and output stage. Different topologies have been proposed by researchers for realizing PET structure [1-7].

This paper aims to explore of using a new structure for PET which consists of Vienna rectifier as input stage, single-phase square wave high frequency inverter with high frequency transformer and single-phase uncontrolled rectifier as isolation stage. 3-phase 5-level diode-clamped inverter as an output stage.

2. PET Structure:

As mentioned in previous section, power electronic transformer (PET) consists of three main stages, input stage, isolation stage and output stage. The following subsection will present the design details of each stage.

2.1 Input Stage

The input stage of PET is the first stage which connects the PET with the main supply. The aim of this stage is to rectify a 3 – phase AC voltage by converting it to a constant dc voltage and maintain near unity power factor with low THD at the input side.

A 3 – phase controlled rectifier considered in this paper was Vienna rectifier. Due to its capability for improving the power quality, Vienna rectifier became a popular rectifier in recent years. A 3 – phase Vienna rectifier consists of three identical power units and each unit consists of 6 – diodes, one switching device, inductor at the line voltage, and two series connected capacitors with identical values at the output as shown in Fig.1 [8]. Although it is simple in its structure and control, Vienna rectifier with proper control can fulfillments the requirements for constant dc voltage at its output with near unity power factor and low THD at its input [9].

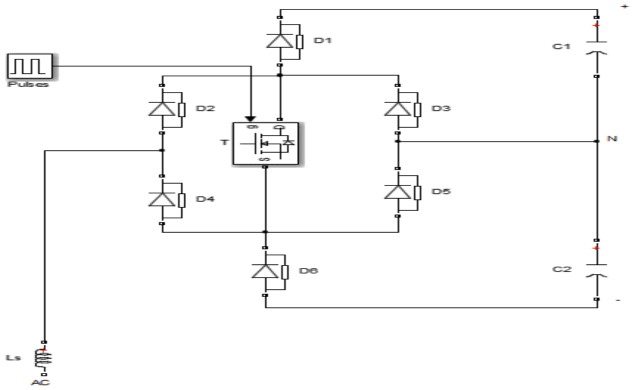


Fig (1): One leg Vienna rectifier structure.

The operation of Vienna rectifier is summarized as follows [8]:

- When $i_s > 0$;

If T is ON, the current flow through D_2, T, D_5, N,

$V_{aN} = 0$.

If T is OFF, the current flow through D_2, D_1, C_1,

$V_{aN} = V_o/2$.

- When $i_s < 0$;

If T is ON, the current flow through D_4, T, D_3, N,

$V_{aN} = 0$.

If T is OFF, the current flow through D_4, D_6, C_2,

$V_{aN} = - V_o/2$.

2. 2 Control algorithm:

The Vienna rectifier requires measuring the voltages and currents at the ac side (input). It also needs to measure the dc bus voltage and the capacitor voltage at the dc side (output). Firstly, the error e_{dc} between the desired DC output voltage V_{dcref} and the measured output voltage V_{dc} is calculated, also the error e_c between the desired voltage at one output capacitor V_{cref} and the measured one V_c is calculated as follows [9].

$$e_{dc} = V_{dcref} - V_{dc} \quad (1)$$

$$e_c = V_{cref} - V_c \quad (2)$$

The error signals produced from (1) and (2) applied to PI controller for each signal to produce reference currents I_{ref1} which corresponds to e_{dc} and I_{ref2} which corresponds to e_c:

$$I_{ref1}(1 - z^{-1}) = k_p e_{dc}(1 - z^{-1}) + k_i e_{dc} \quad (3)$$

$$I_{ref1} = (k_p + k_i \frac{1}{1-z^{-1}}) e_{dc} \quad (4)$$

where z^{-1} represents unit sample delay

Similarly, the following relation for I_{ref2} is established:

$$I_{ref2} = (k_p + k_i \frac{1}{1-z^{-1}}) e_c \quad (5)$$

Now, in order to have maximum power factor at the supply side, instantaneous supply current $i_{s(a, b, c)}$ must keep track the supply voltage $v_{s(a, b, c)}$ by obtaining the normalized instantaneous supply voltage:

$$U_{ns(a,b,c)} = \frac{v_{s(a,b,c)}}{V_{s(a,b,c)m}} \quad (7)$$

Then, multiply each of the normalized voltage by the current obtained in (6) to produce the reference supply currents:

$$i_{sa}^* = I_{rft} \times U_{nsa} \quad (8)$$

$$i_{sb}^* = I_{rft} \times U_{nsb} \quad (9)$$

$$i_{sb}^* = I_{rft} \times U_{nsb} \quad (10)$$

The reference currents produced from (8-10) are compared with the measured supply currents (i_{sa}, i_{sb}, i_{sc}) respectively and the resulting error for each is applied to hysteresis relay with hysteresis band (h). The output of relay which is either 0 or 1 is fed as a gate pulse to the power transistor under the following logic conditions:

(1) *if $i_{s(a,b,c)}^* > 0$, then (not output of relay will pass) else (output of relay will pass)*

(2) *if $V_{dc} < V_{dcref}$ then pass (relay output) else pass (1) to the gate of transistor*

The schematic diagram of the control algorithm for one leg of Vienna rectifier is shown in Fig.2.

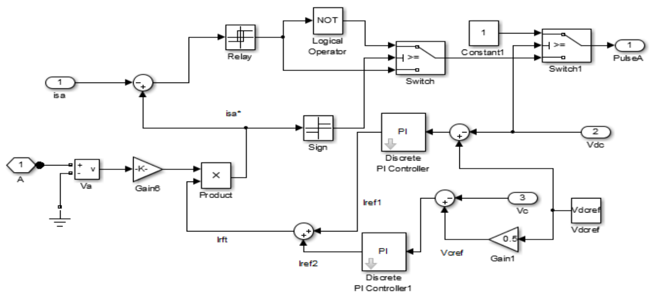


Fig (2): Control algorithm for Vienna rectifier.

2.3 Isolation Stage:

The second stage in Power Electronic Transformer is the isolation stage. The main task of this stage is to perform a transformation from medium dc voltage to low dc voltage through high frequency transformer to guarantees the isolation between load side and source side. According to this aim, isolation stage consists of single phase full – bridge high frequency inverter, high frequency power transformer and single phase full – bridge rectifier.

The challenge in this stage is HF transformer design. The backbone of transformer design is the volt-ampere rating. The parameters that determines the rating of transformer are; core area Ac (m^2), conductor area Ae (m^2), current density J (A/m^2), peak flux density Bm (T) and operating frequency f (Hz). The relationship which relates the transformer rating with its parameters is as follows [1-2]:

$$VA = 2.22. K. f. A_c. A_e. J. B_m \qquad (11)$$

Where K is the copper fill factor.

From (11), a relation between the operating frequency and the size of transformer is obtained as follows:

$$A_c. A_e \propto \frac{VA}{B_m.f.J} \qquad (12)$$

From (12), increasing of frequency leads to reduce the size of transformer, but as the operating frequency increase the core losses increase too. In this paper 1 KHz has been considered as the operating frequency of HF transformer.

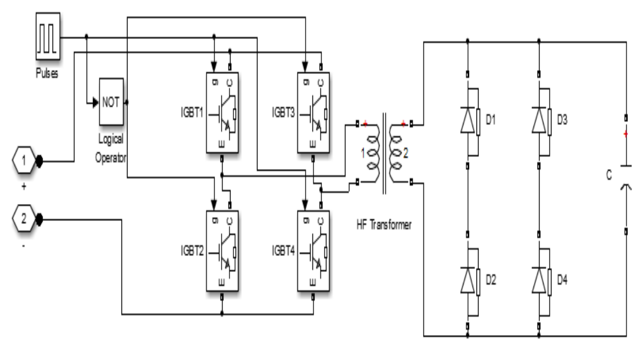


Fig (3): Isolation stage configuration

The frequency of the inverter output voltage is controlled by the frequency of pulses which is set to 1 KHz. The configuration diagram of the isolation stage is shown in Fig. (3).

2.4 Output Stage:

Multi-level inverter which starts by three-level inverter [10], produces more stepped output voltage as its number of level increase. There are three different structure have been proposed for multi-level inverters: diode-clamped (neutral-clamped); capacitor clamped (flying capacitors); and cascaded multi-cell with separate dc sources. In this paper 5-level diode clamped inverter is considered as the output stage of PET. Fig. 4 shows one-leg 5-level diode-clamped inverter.

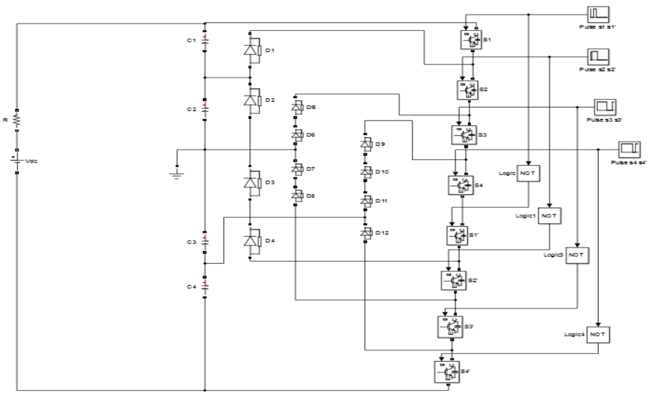


Fig (4): one leg 5-level diode-clamped inverter.

The voltage across each capacitor in Fig.4 is Vdc/4 therefore, the stress voltage for each switching device (s1-s4') is limited to one quarter of the dc voltage.

The control strategy applied to diode-clamped inverter shown in Fig.4 aims to synthesize the stair case output voltage v_{an}. The output voltage of the inverter can be obtained by five switch combination explained in table1 [10].

Table1: Switching Pattern of Inverter

V_{an}	S_1	S_2	S_3	S_4	S_1'	S_2'	S_3'	S_4'
$\frac{V_{dc}}{2}$	ON	ON	ON	ON	OFF	OFF	OFF	OFF
$\frac{V_{dc}}{4}$	OFF	ON	ON	ON	ON	OFF	OFF	OFF
0	OFF	OFF	ON	ON	ON	ON	OFF	OFF
$-\frac{V_{dc}}{4}$	OFF	OFF	OFF	ON	ON	ON	ON	OFF
$-\frac{V_{dc}}{2}$	OFF	OFF	OFF	OFF	ON	ON	ON	ON

Table 1 has been realized for 3-phase inverter by enforcing the pulses to occur in the specified instances to produce the required output voltage level and ensure the phase difference between adjacent phases.

In order to examine the functionality of PET, its stages are embedded in blocks and arranged as shown in Fig.5. Input stage block contains three-phase Vienna rectifier and its control circuit as explained previously. Isolation stage block represents the set of inverter, HF transformer and rectifier. Output stage consists of three-phase diode-clamped inverter and its control circuit. Input-output voltages of each stage is illustrated in table2.

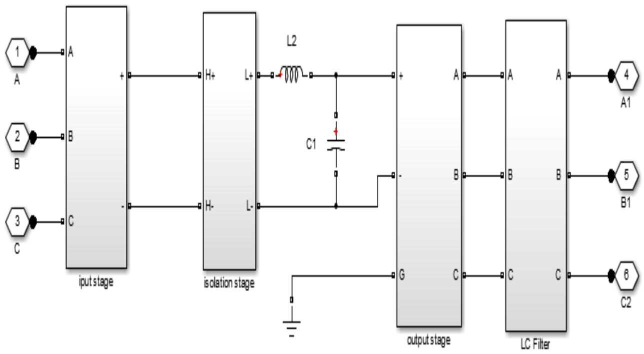


Fig (5): PET structure.

Table2: Input/output voltages of PET stages

Stage	Input Voltage	Output Voltage
Input	11 KV rms, 50 Hz, 3-phase	15 KV DC
Isolation	15 KV DC	750 V DC
Output	750 V DC	220 V rms, 50 Hz 3- Phase

3. PET Design parameters:

In this paper the design parameters considered for PET are shown in table 3.

Table 3: PET design parameters

Parameter	Value
Supply voltage	11 Kv
PI controller parameters: Kp Ki	 0.84 200
Limiter level	10
Hysteresis band	30
Capacitances	3000 μF
Inductances	100 mH
Sampling time Ts	1μsec

4. Simulation Results:

The behavior of the proposed PET has been verified by simulation using MATLAB/SIMULINK. Verification process is performed by testing the performance of input stage, isolation stage and the output stage. Fig. (6) shows simulation results of Vienna rectifier in steady state as the input stage, from Fig.6 it can be shown a high performance of supply side (the input of the rectifier) from power utilization point of view (high power factor of 0.96), while Fig.7 shows reduction in low order harmonics (3rd and 5th) of the supply current.

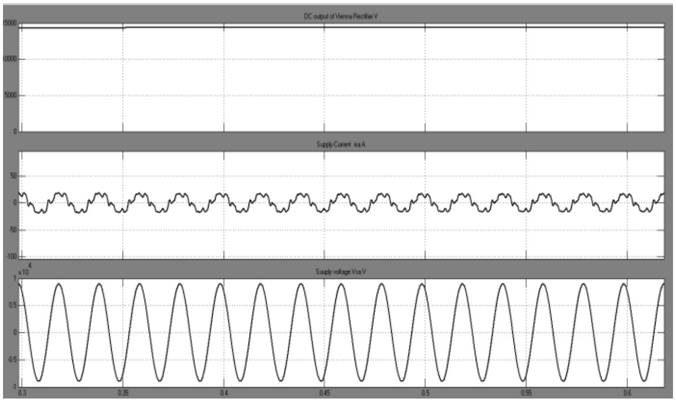


Fig.6: Input stage: Output dc voltage (upper) Supply current (middle) and supply phase voltage (lower)

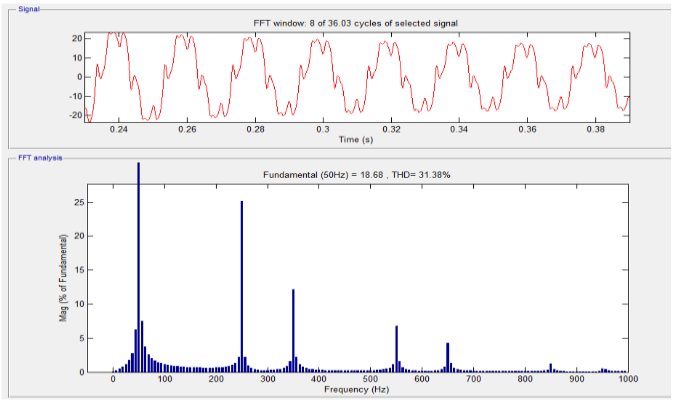


Fig.7: Harmonic distortion of the supply current.

Fig.8 shows the performance of the isolation stage which converts the dc voltage (output of the Vienna rectifier) to high voltage high frequency (1KHz) square wave by high frequency single phase inverter. This voltage is transformed to low voltage high frequency square wave by HF transformer. Finally, this voltage is rectified by uncontrolled rectifier.

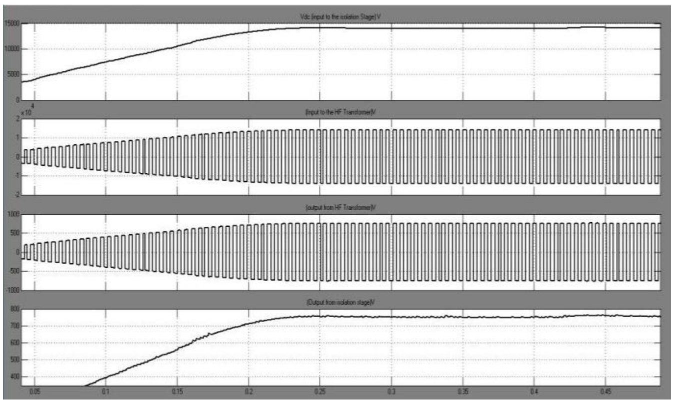


Fig.8: Isolation stage voltages.

Fig.9 shows the load voltage and current produced by the output stage (diode-clamped inverter), high power utility indicated in this figure by near unity power factor. Low THD of the load current has been verified as shown in Fig.10.

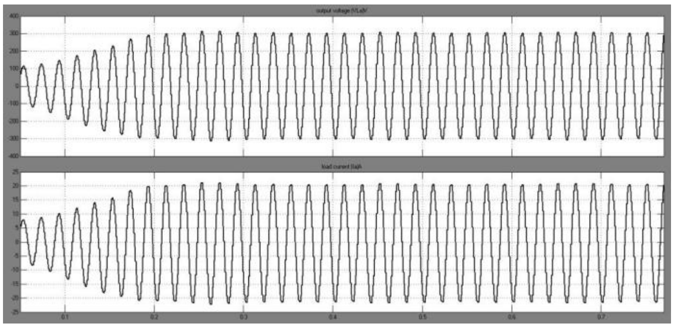


Fig.9: Load Voltage and current.

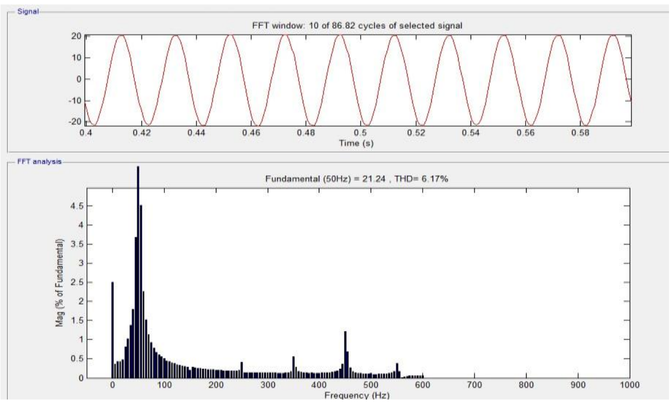
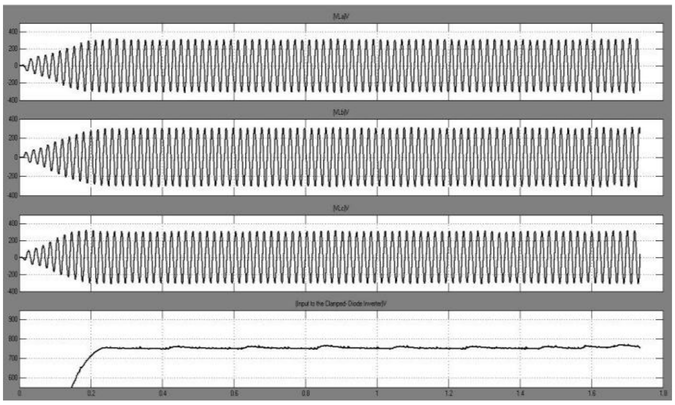


Fig (10): Harmonic Distortion of the load current

Fig.11 illustrates the three phase load voltages and the input to the inverter, the load considered in this case is (10 KW, 2KVAR positive and 100 VAR negative).



Fig(11): Three-Phase voltages at the with the dc input to the inverter.

5. Distribution system based on PET:

In this section the behavior of the distribution system based on PET configuration has been tested by simulation. The feeder voltage is 11KV (rms) 50 Hz and the end user voltage is 400V (rms) 50 Hz. The load is assumed to be located in three positions with different values. The system configuration is shown in Fig.12.

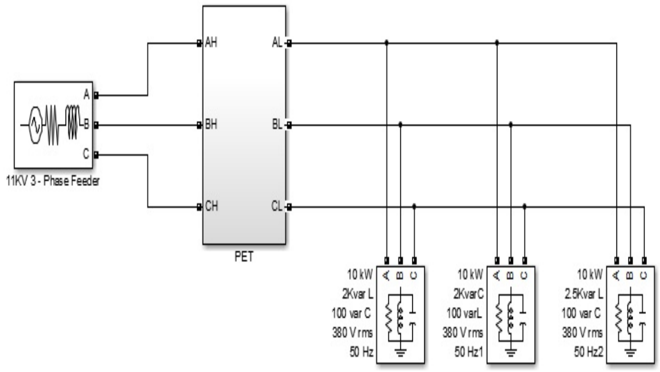


Fig (12): Distribution system based on PET

A comparison between conventional and PET distribution system was performed and the results are shown in table 3 which indicate a significant improvement of input and output power factors when using PET system.

Table3: Comparison between Conventional transformer and PET

Load			Conventional System		PET System	
Active WATT	Positive VAR	Negative VAR	Input Power Factor	Output Power Factor	Input Power Factor	Output Power Factor
10000	100	2000	0.84	0.96	0.97	0.98
10000	2000	100	0.82	0.84	0.96	0.98
10000	2500	100	0.8	0.82	0.95	0.97
Combined Loads			0.803	0.725	0.99	0.98

6. Conclusions:

In this paper, a new structure of PET has been proposed which is employs three-phase Vienna rectifier as an input stage. The isolation stage was configured by using static converters connected to the input and output of high frequency transformer. The output stage of PET is realized by using three-phase 5-level diode clamped inverter. Simulation results show that a high flexibility and power quality can be achieved by using PET comparing with the using of conventional transformer in electric distribution system.

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