Research Journal of Applied Sciences, Engineering and Technology 7(9): 1734-1743, 2014
DOI:10.19026/rjaset.7.457
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: March 04, 2013 Accepted: March 29, 2013 Published: March 05, 2014

Research Article

Optimal Analysis and Design of Power Electronic Distribution Transformer

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Abstract: This study proposes a new design of Power Electronic distribution Transformer (PET) by using an intelligent program to get an optimum HF operation, which leads to maximum efficiency. This PET has three stages; the input stage consists of three phases, three level PWM rectifier and isolation stage employing three level half bridge convertor connected with high frequency transformer. The output stage has a matrix converter. This new design of PET has the advantage of improving power factor, voltage sags, voltage swell, reactive power compensation, eliminating harmonic and controlling and Protecting its self (PET) with minimum size, compared to the traditional transformer. The software like MATLAB and Artificial Neural Network will be used to analyze and simulate the PET.

Keywords: Converters, high frequency switching, magnetic component, optimization, power electronic transformer

INTRODUCTION

Transformers are important equipment in power distribution system as well as in power electronic system. They can step down high voltages in transmission at substations or step up currents to the needed level of end-users. Additionally, many functions, like, isolation, noise decoupling or phase-shifting can be achieved through transformers. The traditional distribution transformer has many disadvantages including being heavy and bulky, secondary voltage varies with the load and input voltage, lack of self protection, having no ability of voltage and current control, not having an intelligent function and the expensive components in electrical power system (Ratanapanachote, 2004).

In this study, a new type of Power Electronics distribution Transformer (PET) is proposed, which realizes the voltage transformation, galvanic isolation and power quality improvements in one device. The proposed PET design is fundamentally different and more complete approach by using power electronics on the primary and secondary sides of the transformer. Several features such as instantaneous voltage regulation, voltage sags compensation and power factor correction can be combined into PET. In addition, the PET is environmentally friendly since no liquid dielectrics are used for cooling. PET can be equipped with advanced communication interface that includes smart metering, diagnostics and distance control features (Subramanya and Anjaneyulu, 2012). The distribution transformer can be classified as shown in Fig. 1.

The prominent challenges in the new design of PET are to achieve smaller core size, higher power quality, higher efficiency and minimum losses. The main challenge is how to increase the efficiency of PET. The general objective of this research is to introduce and elaborate a new design approach for a PET system that can improve the performance of commercial power electronic transformers. In particular this study aims at:

- Design a new PET
- Optimize the design to achieve best trade-offs of highest efficiency, highest power quality, minimum size and minimum losses
- Prototyping and experimenting the design

LITERATURE REVIEW

This section presents the different topologies for PET, in recent 30 years. The first idea of a power electronic transformer has been introduced by Navy researchers 1980, that consisted of an AC/AC buck converter as shown in Fig. 2 to reduce the input voltage to a lower one (Brooks, 1980). This was followed in 1995 by a similar Electrical Power Research Institute (EPRI) sponsored effort (Resischi, 1995). Both of these efforts yielded working prototypes, but they operated at power and primary voltage levels that were orders of magnitude below utility distribution levels.

In1996 the next attempt of a High Frequency (HF) AC link, termed an electronic transformer, was proposed. In this approach, the line side AC waveform is modulated into a HF square wave coupled to the

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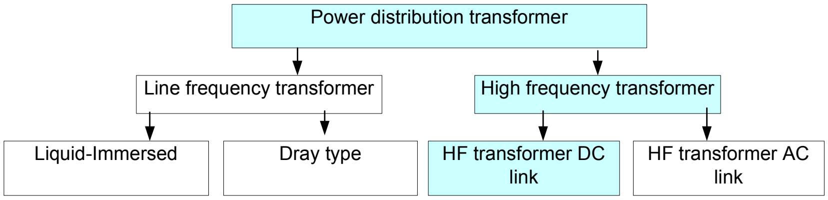


Fig. 1: Type of distribution transformers

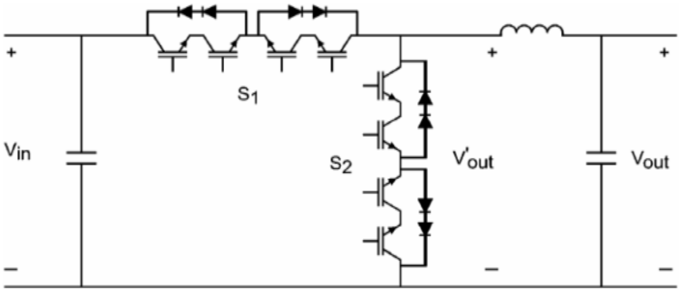


Fig. 2: AC/AC buck converter (Subramanya and Anjaneyulu, 2012)

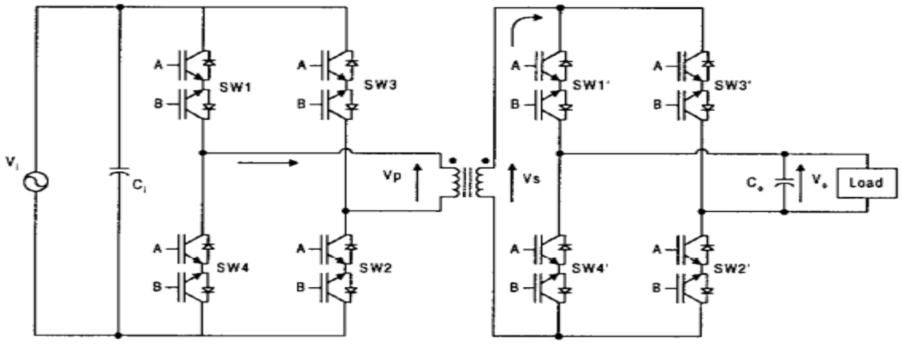


Fig. 3: Power electronic transformer using HF AC link (Harada, 1996)

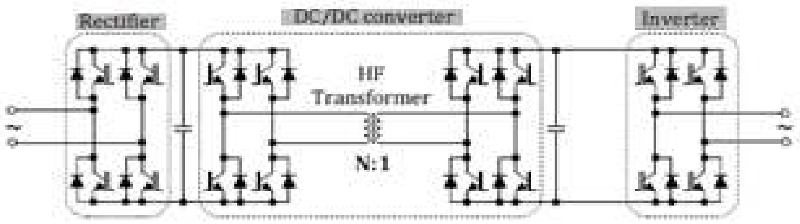


Fig. 4: Power Electronics Transformer (PET) with DC link (Ronan *et al*., 2002)

secondary of the HF transformer and again is demodulated to its AC form by a synchronous converter. The schematic (Shown in Fig. 3) has a benefit of reducing the transformer size and weight and the stress factor more reasonably. But it does not provide any benefit in term of control and power factor improvement and may not protect critical loads from momentary power interruptions due to the lack of an energy storage system (Harada, 1996; Kang *et al*., 1999; Krishnaswami and Ramanarayanan, 2005).

Figure 4 shows that the other type is a three-part design that utilizes an input stage, an isolation stage and an output stage, as addressed in Ronan *et al*. (2002), Iman-Eini and Farhangi (2006), Iman-Eini *et al*. (2008), Maitra *et al*. (2009), Wang *et al*. (2005) and Jih-Sheng *et al*. (2005). The first stage is an AC/DC converter which is utilized to form the input current, to correct the input power factor and to regulate the voltage of the primary DC bus. The second stage is an isolation stage which provides the galvanic isolation between the primary and secondary side. In the isolation stage, the DC voltage is converted to a high frequency square wave voltage, coupled to the secondary of the HF transformer and is rectified to form the DC link voltage.

Table 1: Literature review summary

Authors/year	Title	Type of PET	Result	Issue
Brooks (1980)	Solid state transformer concept development	Buck converter	Reduce the input voltage to a lower one	Low voltage level The lack of magnetic isolation The stress factor is very high
Resischi (1995)	Proof of the principle of the solid-state transformer and the AC/AC switch mode regulator	Buck converter	Reduce the input voltage to a lower one and stress factors	Low voltage level Not have an isolation transformer No DC bus
Harada (1996)	Intelligent transformer	HFAC link	Reducing the transformer size and weight Controlling voltage and power by phase difference control Stress factor is more reasonable	Not provide any benefits such as instantaneous voltage regulation and voltage sags compensation due to lack of energy stage system
Kang *et al*. (1999)	Analysis and design of electronic transformers for electric power distribution system	HF AC link	Reduce size, losses, higher efficiency and Better voltage regulation	This system doesn't provide any benefits in terms of control or power-factor improvement No DC bus Overall efficiency 80%
Ronan *et al*. (2002)	A power electronic-based distribution transformer	HF DC link	Have the benefit in term of control, power factor improvement. Protect critical loads and energy storage system	Series or parallel connection of converter had been used this lead low efficiency and reliability
Jih-Sheng *et al*. (2005)	Multilevel intelligent universal transformer for medium voltage applications	HF DC link	This approach can perform different power quality functions and provide galvanic isolation Isolate a disturbance from either source or load	Different voltage due to multilevel High cost and accept efficiency
Jih-Sheng *et al*. (2006)	Performance of a distribution intelligent universal transformer under source and load disturbances	HF DC link	Bring prototype PET and make test under voltage sag and fault	Lowe efficiency due to core losses
Iman-Eini and Farhangi (2006)	Analysis and design of power electronic transformer for medium voltage levels	HF DC link	Have the benefit in term of control, power factor improvement. Protect critical loads and energy storage system	They need too many power electronic converter and DC link electrolytic capacitors
Iman-Eini *et al*. (2008)	A power electronic based transformer for feeding sensitive loads	HF DC link	Have the benefit in term of control, power factor improvement. Protect critical loads and energy storage system	Series or parallel connection of converter had been used this lead low efficiency and reliability
Maitra *et al*. (2009)	Intelligent universal transformer design and applications	HF DC link	Maintain the input voltage balance among different module	Lowe efficiency due many components
Ling *et al*. (2011)	An effective power electronic transformer applied to distribution system	HF DC link	Reduces the voltage stress Rating of components	Lowe efficiency due many components
Subramanya and Anjaneyulu (2012)	Modeling and simulation of AC/AC matrix converter based power electronic transformer for power quality improvement	HF DC link	Reduction the number of components	Increasing efficiency while reduces power quality The voltage stress factor
Xinyu *et al*. (2012)	Research of three-phase single-stage matrix converter for power electronic transformer	AC Link	Voltage regulation is only 0.5-1	The THD is higher

The output stage is a voltage source inverter which produces the desired AC waveforms. These types enhance the flexibility and functionality of the electronic transformers owing to the available DC links. This approach can perform different power quality functions and can provide galvanic isolation but they need either too much power electronic converters or DC-link electrolytic capacitors. The main disadvantage of this topology is the large number of components which results in possibly lower efficiency and reliability. Moreover in the near future it may be possible to be commercialized. The literature review data are summarized in the Table 1.

METHODOLOGY

This study is suggested to be carried out in three steps, which are:

Phase A:

- **Literature review:** The state of the art and basic concepts of knowledge will be revised while related literate and relevant data of PET will be collected. Consequently, the main feature of the proposed work will be pointed out.

Phase B:

- **Simulation and theoretical analysis:** MATLAB ANN software will be used to obtain the optimum PET design parameter and then the efficiency result will be checked against the traditional transformer.
- Design the closed loop control for PFT.
- **Testing:** PET system will be tested under different load condition.
- The full scale prototype will be made for testing and the result will be compared with theoretical analysis and simulation.

Phase C:

- **Analysis of the result:** The results arising from step B above are tabulated and analyzed.
- Conclusion and recommendations will be drawn from the analysis.

PROPOSED TOPOLOGY

The new proposed topology of power electronic transformer will have a three stages including; an input stage, isolation stage and output stage, as shown in Fig. 5. The input stage consists of three phase, three level PWM rectifier that reduces the stress ratio of the component, where the reactive power and high-voltage dc-link voltage closed-loop controls provide the ability to adjust the reactive power and stabilize the dc-link voltage in the high-voltage side and improve the efficiency. The isolation stage employs three level half bridge convertor connected with high frequency transformer. The output stage has a matrix converter that is used to replace the rectifier and the inverter to reduce the isolation stage component resulting in an efficiency improvement. On the other hand, the optimum design of HF transformer is done by ANN to reduce the losses.

PET mathematical model: By analyzing the new topology of PET, the structure consists of the input stage, middle stage and output stage (Fig. 6 and 7).

Before developing the PET models, we assume that the power system is symmetrical and operates under a three phase balanced condition. By neglecting the VSCs losses, the dynamic differential equations of VSC-1, VSC-2 and the modulating-demodulating block are (Wang *et al*., 2007):

$$L_{E1}\frac{dI_{E1}}{dt} = u_1 - u_{E1} \tag{1}$$

$$L_{E2}\frac{dI_{E2}}{dt} = u_2 - u_{E2} \tag{2}$$

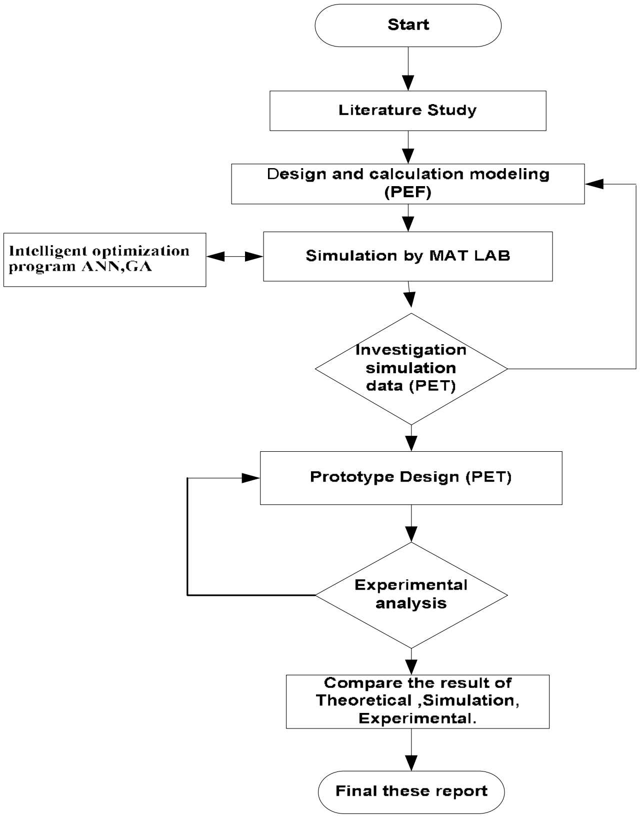


Fig. 5: Methodology flow chart

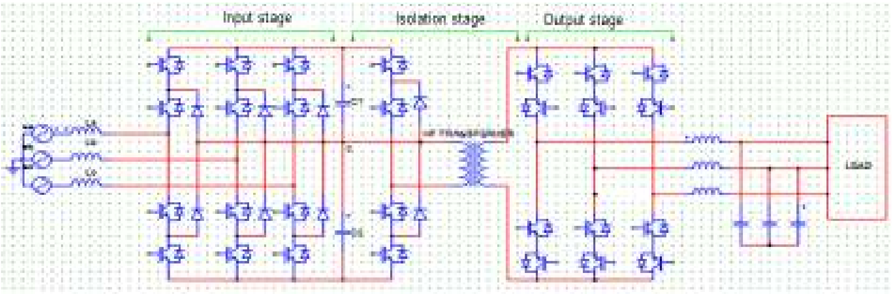


Fig. 6: The proposed topology of PET

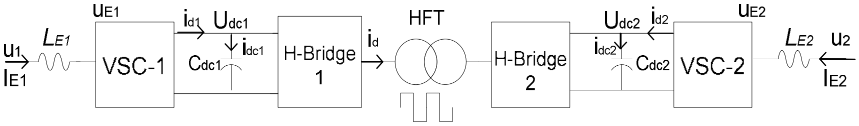


Fig. 7: Physical model of PET

$$C_{dc1}\frac{dU_{dc1}}{dt} = i_{dc1} \tag{3}$$

$$C_{dc2}\frac{dU_{dc2}}{dt} = i_{dc2} \tag{4}$$

where, L_{E1} and L_{E2} are the interface inductances, I_{E1} = [i_{E1a},i_{E1b}, i_{E1c}] and I_{E2} = [i_{E2a}, i_{E2b}, i_{E2c}] the line current vectors in the primary and secondary sides, u_{E1} = [u_{E1a}, u_{E1b}, u_{E1c}] and u_{E2} = [u_{E2a}, u_{E2b}, u_{E2c}] the AC terminal voltage vectors in the primary and secondary sides, u_1 and u_2 the system voltage vectors in the primary and secondary sides, C_{dc1} and C_{dc2} the DC link capacitances, U_{dc1} and U_{dc2} the DC link voltages, i_{dc1} and i_{dc2} the capacitor currents, L_d the equivalent inductance of high-frequency transformer and i_d the current through L_d. The current and voltage variables are expressed as follows:

$$i_{dc1} = i_{d1} - i_d = \sum_{j=a,b,c} i_{E1j} d_{E1j} - i_d \tag{5}$$

$$i_{dc2} = i_{d2} - i_d = \sum_{j=a,b,c} i_{E2j} d_{E2j} - i_d \tag{6}$$

$$u_{E1a} = m_{E1} U_{dc1} \cos(wt + \theta_{E1}) \tag{7}$$

$$u_{E1b} = m_{E1} U_{dc1} \cos(wt - (\frac{2\Pi}{3}) + \theta_{E1}) \tag{8}$$

$$u_{E1c} = m_{E1} U_{dc1} \cos(wt + (\frac{2\Pi}{3}) + \theta_{E2}) \tag{9}$$

$$u_{E2a} = m_{E2} U_{dc2} \cos(wt + \theta_{E2}) \tag{10}$$

$$u_{E2b} = m_{E2} U_{dc2} \cos(wt - (\frac{2\Pi}{3}) + \theta_{E2}) \tag{11}$$

$$u_{E2c} = m_{E2} U_{dc2} \cos(wt + (\frac{2\Pi}{3}) + \theta_{E2}) \tag{12}$$

where, d_{E1j} (j = a, b or c) and d_{E2j} (j = a, b or c) are the duty ratio switching functions for *VSC*-1 and *VSC*-2, m and θ the amplitude modulation index and phase angle of the control signal of each *VSC*, respectively and k the transformation ratio of the high-frequency transformer. By applying Park's transformation, the dynamic model of EPT in the d-q rotating reference frame can be given by:

$$L_{E1}\frac{dI_{E1d}}{dt} = \omega L_{E1} i_{E1q} + u_{1d} - u_{E1d} \tag{13}$$

$$L_{E1}\frac{dI_{E1q}}{dt} = \omega L_{E1} i_{E1d} + u_{1q} - u_{E1q} \tag{14}$$

$$L_{E2}\frac{dI_{E2d}}{dt} = \omega L_{E2} i_{E2q} + u_{2d} - u_{E2d} \tag{15}$$

$$L_{E2}\frac{dI_{E2q}}{dt} = \omega L_{E2} i_{E2d} + u_{2q} - u_{E2q} \tag{16}$$

$$\frac{dU_{dc1}}{dt} = \frac{3m_{E1}}{2C_{dc1}}(i_{E1d}\cos\theta_{E1} + i_{E1q}\sin\theta_{E1}) - i_d \tag{17}$$

$$\frac{dU_{dc2}}{dt} = \frac{3m_{E2}}{2C_{dc2}}(i_{E2d}\cos\theta_{E2} + i_{E2q}\sin\theta_{E2}) - i_d \tag{18}$$

$$L_d\frac{di_d}{dt} = U_{dc1} - U_{dc2} \tag{19}$$

A new topology model of power electronic transformer, after development is shown in Fig. 8.

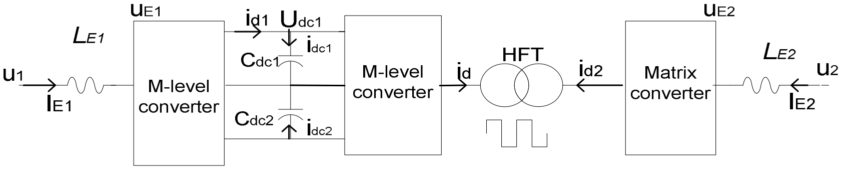


Fig. 8: Physical model of a new proposed PE

The input stage mathematical models are:

$$L_{E1}\frac{dI_{E1d}}{dt}=\omega L_{E1}i_{E1q}+u_{1d}-u_{E1d} \tag{20}$$

$$L_{E1}\frac{dI_{E1q}}{dt}=\omega L_{E1}i_{E1d}+u_{1q}-u_{E1q} \tag{21}$$

The output stage mathematical models are:

$$L_{E2}\frac{dI_{E2d}}{dt}=\omega L_{E2}i_{E2q}+u_{2d}-u_{E2d} \tag{22}$$

$$L_{E2}\frac{dI_{E2q}}{dt}=\omega L_{E2}i_{E2d}+u_{2q}-u_{E2q} \tag{23}$$

The mathematical models of the isolation stage are:

$$\frac{dU_{dc1}}{dt}=\frac{3m_{E1}}{2C_{dc1}}(i_{E1d}\cos\theta_{E1}+i_{E1q}\sin\theta_{E1})-i_d \tag{24}$$

$$\frac{dU_{dc2}}{dt}=\frac{-3m_{E2}}{2C_{dc2}}(i_{E2d}\cos\theta_{E2}+i_{E2q}\sin\theta_{E2})-i_d \tag{25}$$

$$L_d\frac{di_d}{dt}=U_{dc1}-u_{E2} \tag{26}$$

where,

$$U_{dc}=U_{dc1}-U_{dc2} \tag{27}$$

Controlling input rectifier: The main functions associated with the rectifier control are shaping the input current, controlling the input power factor and keeping the DC-link voltage at the desired reference value. The control scheme developed in rotating d-q reference frame would lead to better performance (Wang *et al.*, 2007). The mathematical models of the input stage are:

$$L_{E1}\frac{dI_{E1d}}{dt}=\omega L_{E1}i_{E1q}+u_{1d}-u_{E1d} \tag{28}$$

$$L_{E1}\frac{dI_{E1q}}{dt}=\omega L_{E1}i_{E1d}+u_{1q}-u_{E1q} \tag{29}$$

To implement the above functions, in the outer-loop control, the feedback DC voltage is compared to the reference value. The difference is then passed through the PI controlled to get the reference value of d-axis current. When the reference value of q-axis current is set to zero, the rectifier can achieve unity power factor operation. In the inner-loop, three-phase input currents are transformed into d-axis current and q-axis current components in the synchronous rotating d-q reference frame. The components are compared with the reference values of both d-axis current and q-axis current, the differences then formed the modulated wave signal by the PI controller. The three-level rectifier control principle is shown in Fig. 9.

The output stage control: In the output stage, three-phase matrix converter outputs the constant-amplitude and constant-frequency voltage to the load through the output voltage closed-loop control. When the load changes within a certain range, the PET should maintain the amplitude of the output voltage. The control principle diagram is shown in Fig. 10. The three-phase output voltages are converted to the d-axis u_{E2d} and q-axis u_{E2q} in the synchronous rotating d-q reference frame, respectively. The voltage is then compared with the reference values of $u_{E2\ dref}$ and $u_{E2\ qref}$. The modulated signal is formed by the PI controller. The PWM control algorithms realize the control of inverter switches.

HFT design procedure: The starting point of transformer design procedures is rating design requirement (V_p and I_p). The variables parameter are core area, conductor area, flux density, current density and frequency operation. The voltage ampere rating, S of transformer defined as:

$$S=I_PV_P \tag{30}$$

And the primary voltage, V_P:

$$V_P=N_PA_{cor}\omega B \tag{31}$$

The primary current, I_P:

$$I_P=J_PA_{cup} \tag{32}$$

Then:

$$S=I_PV_P=\frac{N_PA_{cor}\omega J_{rms}A_{cup}}{\sqrt{2}} \tag{33}$$

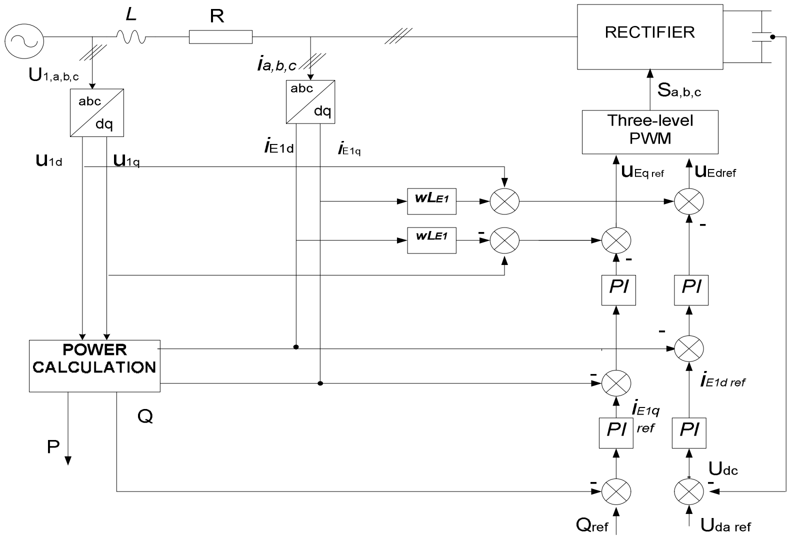


Fig. 9: Input stage control

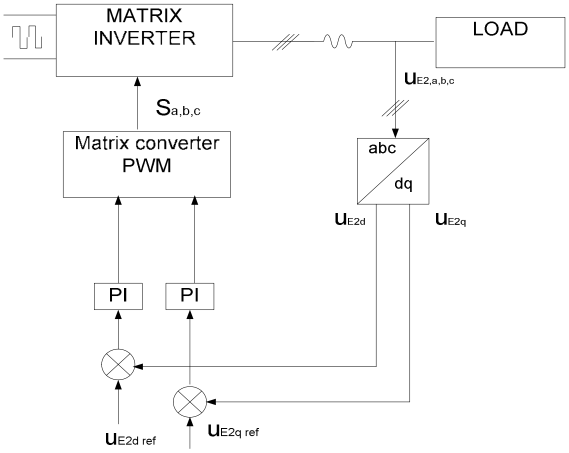


Fig. 10: Output stage control

where,

$$A_{cup} = \frac{K_{cu}A_w}{2N_p} \tag{34}$$

where, k_{cu} = copper fill factor:

$$K_{cu} = \frac{NA_{cu}}{A_w} \tag{35}$$

And A_W is the winding area:

$$A_w = A_{cup} + A_{cus} = \frac{NA_{cup}}{K_{cup}} + \frac{NA_{cus}}{K_{cus}} \tag{36}$$

Then:

$$S = I_pV_p = 2.22K_{cu}fA_{cor}A_wJ_{rms}B \tag{37}$$

where, N the number of turns, A_{cor}, A_w, A_{cu} the core area, winding area and copper area respectively, f the frequency, B flux density and J_{rms} the current density. Core and winding losses and transformer temperature rise are expressed in terms of geometry, material, winding and excitation parameters.

Hysteresis loss (core loss):

$$P_h = Kf^aB^b \tag{38}$$

K, a and b are constants that vary from material to another.

Eddy current loss (Winding loss, P_w):

$$P_w = \frac{R_{ac}}{R_{dc}}K_{cu}(J_{rms})^2 \tag{39}$$

$$P_w = \frac{R_{ac}}{R_{dc}}K_{cu}\frac{(I_{rms})^2}{A_{cu}} \tag{40}$$

where R_{dc} the DC resistance of the winding and R_{ac} the net resistance of the winding.

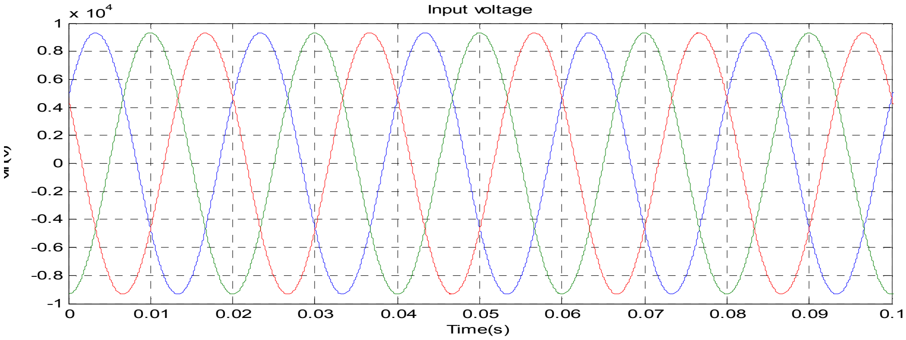
The power dissipated due to thermal, P_s:

$$P_s = \frac{T_S - T_A}{R_\theta(V_{cor} + V_w)} \tag{41}$$

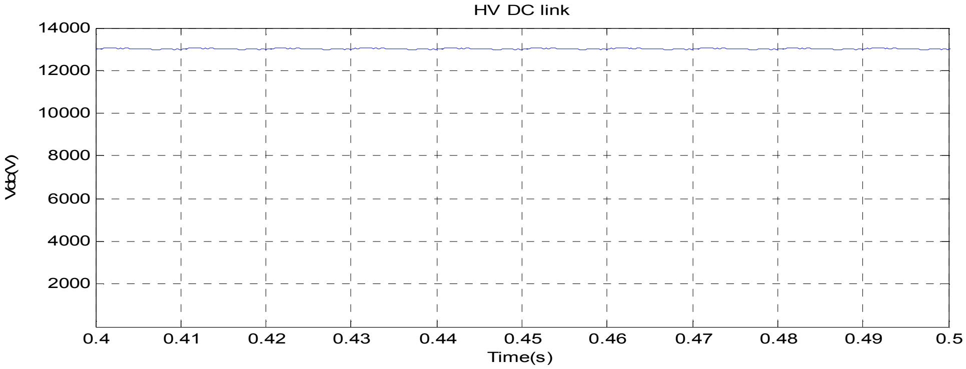
where,

T_S = Maximum surface temperatures

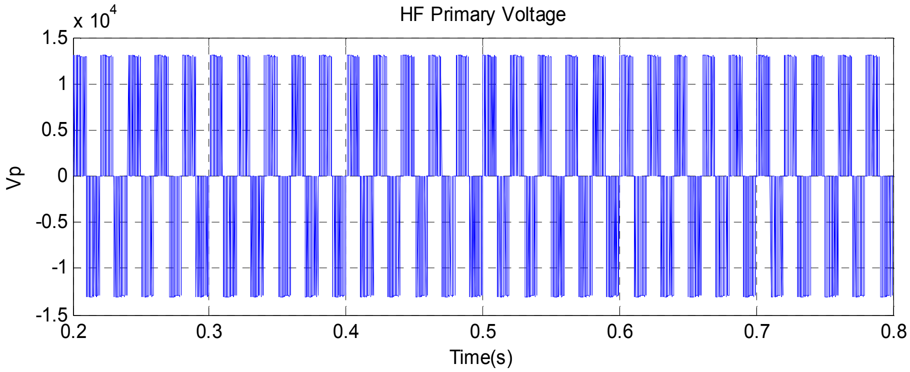
T_a = Ambient temperatures



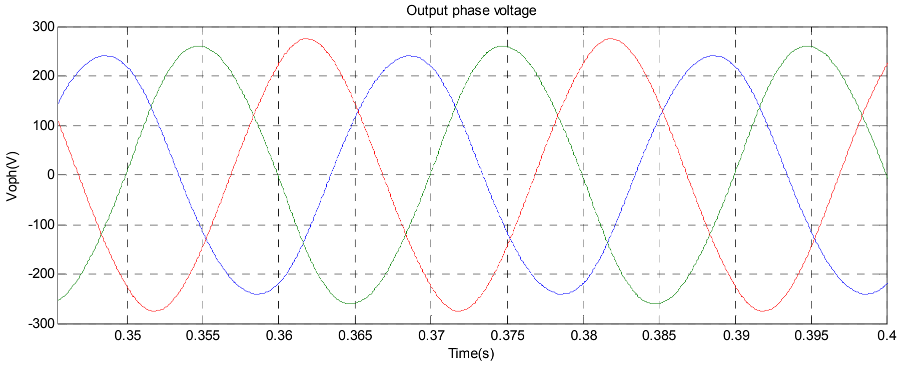
(a) Input voltage of proposed PET



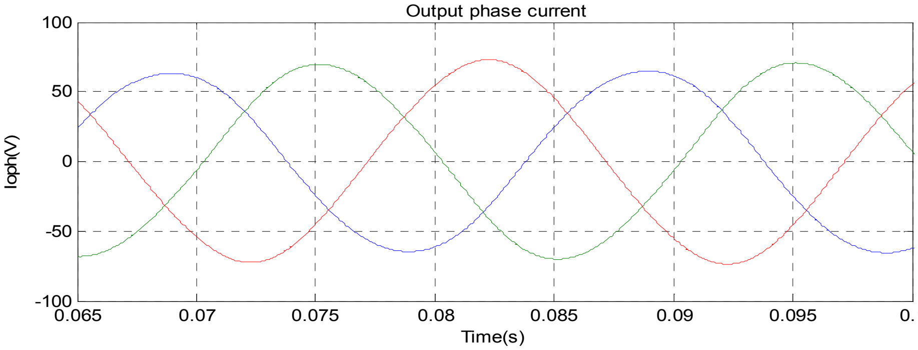
(b) High voltage DC link voltage of proposed PET



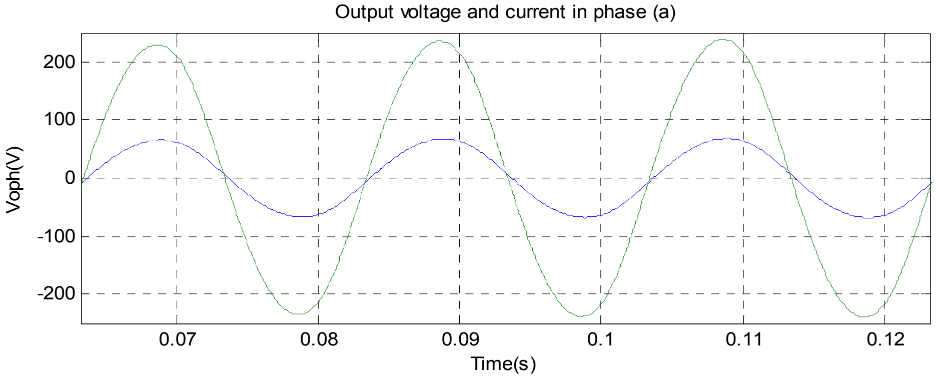
(c) Transformer primary voltage of proposed PET



(d) 3-phase output voltage of proposed PET



(e) 3-phase output current of proposed PFT



(f) The output phase voltage and current of proposed PET

Fig. 11: (a) Input voltage of proposed PET, (b) input voltage of traditional transformer, (c) high voltage DC link voltage of proposed PET, (d) transformer primary voltage of proposed PET, (e) 3-phase output voltage of proposed PET, (f) 3-phase output voltage of traditional transformer, (g) 3-phase output current of proposed PFT, (h) 3-phase output current of traditional transformer, (f) phase voltage and current of proposed PET

$$R_\theta = R_{\theta rad} + R_{\theta conv} = \frac{\Delta T}{5.1A[(\frac{T_S}{100})^4 - (\frac{T_A}{100})^4]} + \frac{1}{1.3A}(d_{vert}) \tag{42}$$

where,

R_θ : The thermal resistance

$R_{\theta rad}$: The resistance due radiation

$R_{\theta cov}$: The resistance due to convection

d_{vert} : Vertical height

The efficiency of a transformer can be calculated by the following equation:

$$\eta = \frac{VI\cos\phi}{VI\cos\phi + P_h + P_w + P_s} \tag{43}$$

where, $\cos\varphi$ is the power factor.

SIMULATION RESULTS

In this section, the load characteristics of the PET are investigated by simulations. The simulation is based on MATLAB/SIMULINK. In the simulation, the primary voltage of PET is 6.6 KV and the output voltage is 415V. The parameters are shown in Table 2.

Table 2: Initial parameter values

Parameter	Value
Line-line input voltage	6.6 KV
Input inductance	2 mH
DC link HV side capacitor	6800 µF
Frequency	1 KHz
Transformer rated	25 KVA
Filter inductance	9 mH
Filter capacitance	680 µF
Load R, L	3.5 Ω., 4 mH

Table 3: Simulation result of output voltage and current in the load side for traditional and new proposed PET

Parameter	Proposed PET
VA rating	25 KVA
Frequency	1 KHz
Input voltage (L.L)	6.6 KV
Output voltage (ph)	236 V
Output current (ph)	65 A

The results of the proposed Power Electronic distribution Transformer (PET) are shown in Fig. 11a shows the input line voltage of PET, (b) shows High voltage DC link of PET, (c) shows power electronic transformer primary voltage and (d) shows the three phase output phase voltage in the load for PET and the three phase current in the load also show in (e) and (f) shows the output voltage and current of PET in phase. As we can see from Fig. 11 and Table 3 the output voltage is 236 V and the output current is 56A. In terms of electrical performance the proposed electronic transformer and conventional transformer are identical, but the power electronic transformer not only used to step down the voltage, but also to improve the power quality of distribution system, that lead to wide application prospect.

CONCLUSION

A new power electronic distribution transformer is proposed, the simulation result shows that the output current and voltage have a better waveform that supports the proposed power electronic transformer system. The optimization of the whole system will be achieved by using close loop control, best core size, optimal frequency operation and reducing the number of components.

ACKNOWLEDGMENT

The author would like to thank the Universiti Teknologi PETRONAS for funding this research project under the “Graduate Assistantship Scheme”.

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