REDUCED SWITCH TOPOLOGY OF POWER ELECTRONIC TRANSFORMER

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Abstract: *This paper proposes a new modular flexible power electronic transformer (FPET). The proposed FPET is flexible enough to meet future needs of power electronic centralized systems. The main feature of the FPET is the independent operation of modules each of which contains one port. Each port can be considered as input or output, because bidirectional power flow is provided. The modules are connected to a common dc link that facilitates energy transfer among modules as well as ports. Therefore, a multiport system is developed, which the ports can operate independently. This merit is important for applications, where input and output voltages are different in many parameters. A comparison study is carried out to clarify the pros and cons of expandable FPET. In addition, the measurement results of a laboratory prototype are presented to verify the capabilities of FPET in providing different output waveforms and controlling load side reactive power.*

INTRODUCTION:

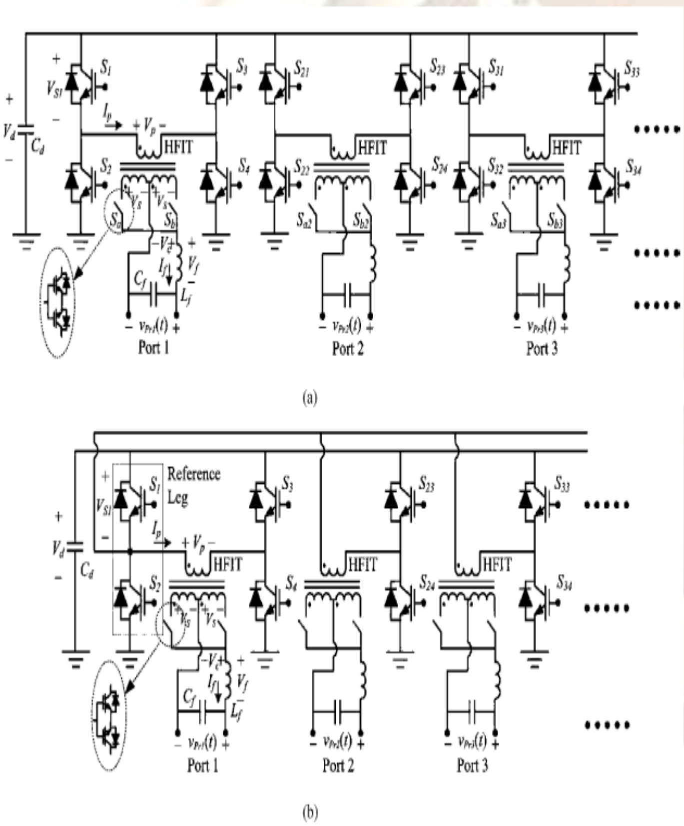
In this paper, a new PET topology named flexible power electronic transformer (FPET) is proposed. As shown in Fig. 1, it is constructed based on modules and a common dc link, which is used to transfer energy between ports and isolate all ports from each other. In this bidirectional topology, each port can be considered as an input or output. Each module consists of three main parts, including modulator, demodulator, and high frequency isolation transformer (HFIT). The modulator is a dc–ac converter and the demodulator is an ac–ac converter; both with bidirectional power flow capability. Each module operates independently and can transfer power between ports [1]-[5].These ports can have many different characteristics, such as voltage level, frequency, phase angle, and waveform. As a result, FPET can satisfy almost any kind of application, which are desired in power electronic conversion systems and meet future needs of electricity networks. Considering this point, it is named flexible. The simulation results of high-voltage application are given to clarify the advantages of the proposed FPET over the recently developed PETs. To show the flexibility of the proposed PET, a prototype is built and tested.

PROPOSED POWER CIRCUIT OF FPET

The proposed circuit is shown in Fig. 2. It should be mentioned that the proposed topology can be expanded by connecting modules in series or parallel to obtain higher voltage or current ratings, and to form star/delta connections for three phase applications.

As shown in Fig. 2(a), each port is composed of a full bridge dc-link inverter (FBDCI), HFIT, and a Cyclo-converter. This topology consists of independent and similar modules and each port can work independently. Thus, the analysis of one port is sufficient to introduce whole topology. The FBDCI (modulator) can operate as an inverter when it converts the dc-link voltage to an ac waveform at the HFIT side. It can operate as an active rectifier when it converts the ac waveform of the HFIT to the dc-link voltage. The FBDCI is used to achieve zero-voltage level, adjustable pulse width, and symmetrical switching. In addition, the number of switches can be reduced to obtain simpler circuit than the latter, shown in Fig. 2(b). In this case, one of the half-bridge circuits can be considered as the reference or master leg. Once gate pulses for the master leg (i.e., switches and) are provided, the gate pulses of the other legs (slave legs) have a phase shift respect to the master leg. Using this control strategy, the number of switches can be reduced to half [10]-[12].

Fig2.Proposed circuit of the FPET (a) Basic topology and (b) reduced switch topology



The modulator can be described as follows:
1) Bi directional power flow capability;
2) Adjustable switching frequency that feet voltage pulses frequency into the pass band of HFIT;
3) Stored energy in the dc link (if the modulator is in active rectifier mode). For cyclo-converters, several circuit topologies can be proposed using unidirectional or bidirectional switches.

In this paper, a typical cyclo-converter with two bidirectional switches operates as the demodulator. The demodulator converts high frequency voltage (i.e.) to low frequency voltage (i.e., Vpr1) and vice versa. The specifications of the demodulator are listed as follows:
1) Bidirectional power flow capability; and
2) Providing zero voltage switching by turning the switches of cyclo-converter ON/OFF, while voltage of HFIT riches to zero.

BALANCING PORTS:

For another solution to regulate voltage of dc link, some ports are considered as "balancing ports" that provide energy to balance dc-link voltage in FPET. One of the main objectives of these kinds of ports is to control voltage level in the dc-link voltage, particularly when over voltage or voltage drop occurs in the dc link. Assuming the i^{th} port is chosen as the *balancing port*, the main component of the cyclo-converter voltage, and output of the port are given as follows:

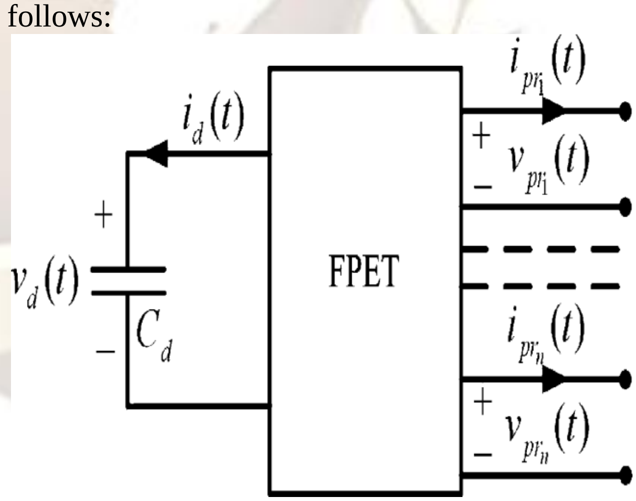


Fig.6. Simplified diagram of FPET

$$v_{c_i}(t) = \sqrt{2}V_{c_i}\ \sin(2\pi f_i t - \phi_{c_i}) \rightarrow\ V_{c_i}\angle\phi_{c_i}$$
$$v_{pr_i}(t) = \sqrt{2}V_{pr_i}\ \sin(2\pi f_i t - \phi_{p_i}) \rightarrow\ V_{pr_i}\angle\phi_{p_i} \qquad 1$$
$$\delta_i = \phi_{c_i} - \phi_{p_i}.$$

The definition of the parameters is given in the Table II. Therefore, neglecting the resistance of output filter inductance, the active power of the port is obtained as follows:

$$P_i = \frac{V_{c_i} V_{pr_i}}{2\pi f_i L_f} \sin\delta_i . \qquad 2$$

Applying the differences between Vd and V_d,Ref as an error signal to a typical PI controller, the

$$\sum_{i=1}^{n} i_{pr_i}(t) v_{pr_i}(t) + v_d(t) i_d(t) = 0. \qquad 3$$

value of required Pi can be estimated. According to [6] and [7], the duty cycles are achieved.

DESIGN PROCEDURE:

A. DC-LINK CAPACITOR

Fig. 6 shows the voltage and currents of all ports and the dc link capacitor. The following equation presents the instantaneous power balance of the losses in FPET.

$$\bar{P} \approx V_{d,\mathrm{Ref}} I_d = -\frac{1}{2}\sum_{i=1}^{n} I_{m_i} V_{m_i} \cos(\phi_i - \theta_i) \qquad 6$$

$$\tilde{P} \approx V_{d,\mathrm{Ref}} C_d \frac{\Delta V_d}{\Delta t} = \frac{1}{2}\sum_{i=1}^{n} I_{m_i} V_{m_i} \cos(2\omega_i t - \phi_i - \theta_i). \qquad 7$$

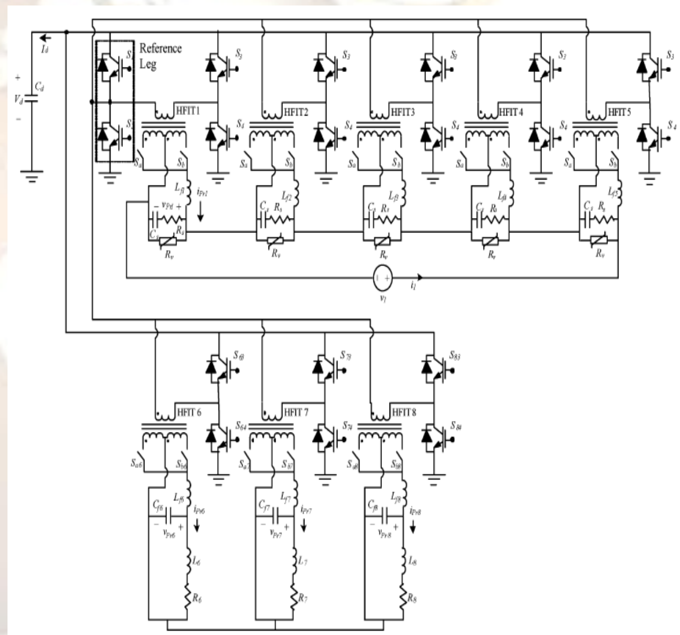


Fig.7. Proposed HV FPET

The voltage and current of ports can have different polarity and directions. If the currents and voltages of ports have sinusoidal waveforms, then (12) can be rewritten as follows:

$$\sum_{i=1}^{n} I_{m_i} \sin(\omega_i t - \phi_i) V_{m_i} \sin(\omega_i t - \theta_i) + v_d(t) i_d(t) = 0. \qquad 4$$

Now, the input power of dc link can be expressed as follows:

$$v_d(t)i_d(t) = \frac{1}{2}\sum_{i=1}^{n} I_{m_i} V_{m_i} \cos(2\omega_i t - \phi_i - \theta_i) - \frac{1}{2}\sum_{i=1}^{n} I_{m_i} V_{m_i} \cos(\phi_i - \theta_i) = \tilde{P} + \bar{P}. \quad 5$$

This input power consists of two components. The first component is the pulsation power $(\tilde{P})$ with angular frequency of 2ωi and the second one is the dc power $(\bar{P})$. Assuming $V_{d,ref}$ as the voltage of capacitor and Id as the average current, (14) can be rewritten as follows:The ripple voltage of the dc-link capacitor (ΔVd) can be approximated as follows:

$$\Delta V_d \approx \frac{1}{C_d}\frac{1}{V_{d,\mathrm{Ref}}}\sum_{i=1}^{n}\frac{P_i}{\omega_i}. \quad 8$$

Thus, the minimum value of Cd can be calculated for the maximum voltage ripple.

B. REFERENCE VOLTAGE OF DC LINK AND WINDING RATIO OF HFIT

From practical point of view, lower dc-link voltage results in lower voltage stress of switches. But according to [17], as Vd, Ref decreases, the voltage ripple increases. In addition, the decrease of the dc-link voltage increases the current of dc link switches. Consequently, by selecting an appropriate dc link reference voltage (Vd,Ref) and the maximum ripple voltage, the minimum dc-link voltage (Vd,min) can be determined. In the worst condition, the lowest dc-link voltage (Vd,min), maximum duty cycle (D = Dmax) and the maximum magnitude of desired.

Table iii: Parameters of pets

FPET	
Parameter	Definition / Value
No. of ports	5 Ports, series connected
f_{HFIT}	2kHz, frequency of HFIT
$L_{f1,2,3,4,5}$	4 mH (total 20mH)
C_d	2200μF
$C_{f6,7,8}$	3×20μF
$L_{f6,7,8}$	3×1.5mH
Load PF	0.8 Load power factor
Load	3×10kW, 3 phases
$V_{d,ref}$	600V
V_1	1900 V rms, 50 Hz; Utility
$N_{1,2,3,4,5}$	1.6, Turns ratio
$N_{6,7,8}$	0.8, Turns ratio
f_{tr}	2kHz, MF transformer frequency
L_b	10mH, Line inductance
$C_i + Cc$	5×2×560μF+680μF, Units capacitors
C_f	3×100μF, Load filter capacitor
L_f	3×1.5mH, Load filter inductance
Load PF	0.8 Load power factor
Load	3×10kW, 3 phases
dc bus Ref.	600V, Common dc bus ref. voltage
v_{in}	1900 V rms, 50 Hz; Utility
n_1:n_2	12:5 MF transformer turns ratio

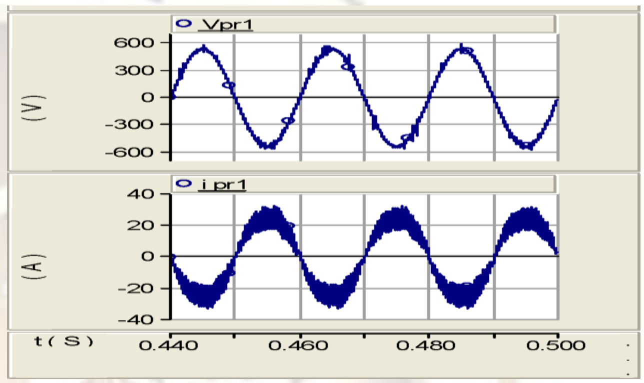


Fig.8. Port voltage and current of HV FPET

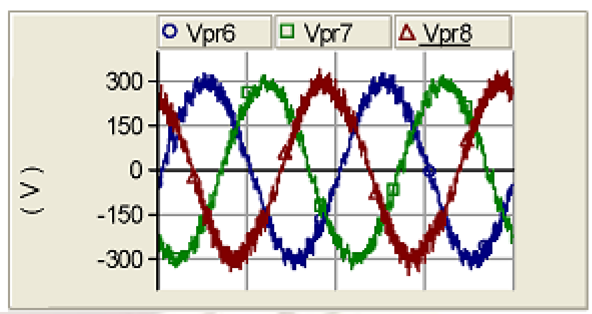


Fig.9. Load voltage of three-phase output.

$$N_i > \frac{V_{i,\max}}{K_c V_{d,\min} D_{\max}} \quad 9$$

Voltage (Vi,max) can determine the winding ratio as follows:

C. MATCHING INDUCTANCE LF

Matching inductance Lf should limit the output current to its maximum acceptable value (Ii,max) during the switching period (Ts). For the ith port, the following assumptions can be considered:

$$\begin{cases} V_s = N_i V_{d,\max} \\ \Delta i_{f_i} < I_{i,\max} \\ V_{pr} = -V_{i,\max} \\ R_{f_i} \approx 0 \end{cases} \quad (10)$$

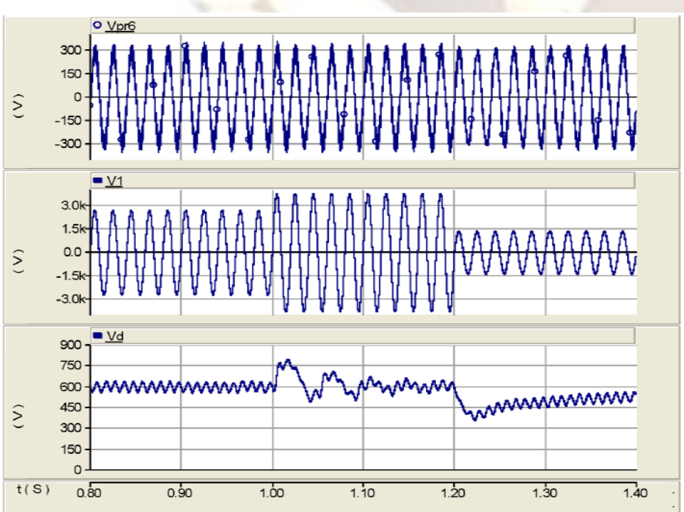
Where $\Delta_i f_i$ is the variation of the cyclo-converter current for one switching period Based on these assumptions, Lf is determined by

$$L_{f_i} \frac{\Delta i_{f_i}}{T_s} \approx (N_i V_{d,\max} + V_{i,\max}) \quad (11)$$

$$L_f > (N_i V_{d,\max} + V_{i,\max}) \frac{1}{f_s I_{i,\max}}. \quad (12)$$

HIGH VOLTAGE APPLICATIONS

In order to provide a HV application, the modules of PETs are connected in series [9], [13], and [14]. The cascaded H-bridge multilevel PET has been proposed in [9]. The advantages of this PET are: the low switching frequency, the low input current harmonics, the power factor correction, and the reduction of the input voltage distortion at the output side. Fig. 7 shows the proposed HV FPET, which should be compared with the PET, suggested in [9]. As can be seen in this figure, the ports one to five, i.e., *P*1, *P*2,. . ., *P*4 are connected in series to increase the rating of the input voltage.



CONCLUSION

Based on the requirement of a flexible power conversion system, FPET is proposed to facilitate many requirements that are expected in power electronic and distribution systems. The proposed topology is flexible enough to provide bidirectional power flow and has as many ports as it is required. For low-voltage application, FPET can correct power factor and can adjust the waveform and frequency of the output voltage. The proposed topology can be expanded for high voltage and high current applications. The dc link plays a significant role to provide energy balance, power management in the circuit and independent operation of ports. The measurement results verify the basic theoretical concepts of this paper. The advantages of the FPET are: bidirectional power flow capability of ports, module-based topology, which can be used in different forms, independent operation of ports, flexibility in power amount and direction in all ports, and double galvanic isolation between each port, as well as using only one storage element.

Table V: Comparison study of fpet and those proposed in [4] & [12]

Definition	$3\phi/3\phi$ FPET (6 port)	[12]	[4]
No. of semiconductor devices	38	22	34
No. of storage capacitors	1	0	4
No. of HF transformers	6	1	1
Bidirectional power flow capability	Yes	Yes	Yes
Cost efficient, regarding the design simplicity, the number of dc link capacitors and the number of transformers	Better	The best	Good
Efficiency regarding the number of switches	Good	The best	Better
Reliability regarding independent operation capability of phases (ports)	The best	Good	Better
Providing desired voltage and current and connecting in series or connecting in parallel to the grid. Suitable for DVR and AF applications	Yes	No	No
Independent capability of providing desired waveform in each phase, and independent capability of active/reactive power adjustment in each phase for UPQC applications	Yes	No	No
Transfer of active/reactive power from one phase to another phase or from one line to another line in power distribution system act as IPFC	Yes	No	No
Providing symmetrical load voltage from an asymmetrical dc/ac sources for UPS application	Yes	No	No
Management of variable low-voltage dc sources suitable for renewable energy applications	Yes	No	No
Providing neutral wire at the input or output sides	Yes	No	No
Design simplicity	Yes; modular structure	No	No
Expandability to achieve higher ratings	Yes; modular structure	No	No

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