International Journal of Advanced Technology in Engineering and Science
Vol. No.4, Issue No. 10, October 2016
www.ijates.com
ijates
ISSN 2348 - 7550

# A VARIABLE REACTOR BASED INTEGRATED POWER QUALITY CONTROLLER FOR MICROGRID

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## ABSTRACT

*A novel variable reactor based on magnetic flux control is proposed in this paper. The system configuration of the novel variable reactor is presented, while its operational principle is analyzed. Based on the developed variable reactor, a novel integrated power quality controller (IPQC) suitable for microgrid is proposed, which can cater for the peculiar requirements of microgrid power quality, such as the harmonic high penetration, frequent voltage fluctuation and overcurrent phenomenon, and bidirectional power flow and small capacity. For the fundamental, the equivalent impedance of the primary winding is a variable reactor or capacitor. For the nth-order harmonic, the equivalent impedance is very high impedance and acts as a "harmonic isolator." The system control strategy is also analyzed in detail. A set of three-phase IPQC has been constructed. The simulation results verify the validity of the novel variable reactor and the IPQC.*


***Keywords*:-** *Microgrid, overcurrent, power quality, transformer, variable reactor.*

## I. INTRODUCTION

Distributed power generation has been emerged as a promising option to meet the growing customer needs for electric power with an emphasis on reliability and environmentally friendly renewable energy. In this context, in order to maximize the operational efficiency of the distributed energy resources (DERs) and take full advantage of distributed power generation, as an effective means of integrating DERs into the traditional power grid, microgrid is presented, which can enhance the local customer power supply reliability and system performance, reduce the impact on large power grid, and minimize the system losses. Microgrid has good environmental and economical benefits and has attracted more and more attentions of power researchers [1]-[6]. However, the power quality problem of microgrid is much more serious than that of the traditional grid because of the intermittency and randomness of DERs, the high penetration between conventional grid and microgrid, the diversity of DERs, load, energy conversion unit, storage, and operating state. Microgrid power quality has the following unique features compared with the conventional power grid [7].

1) Background harmonic of DERs and harmonic high penetration are more serious than those of the traditional grid [17]. The traditional grid has less system background harmonic, and the harmonic is mainly from the nonlinear load. However, in microgrid, in addition to the nonlinear load, DERs and energy storage converter system access to microgrid may also generate harmonics.

2) Bidirectional power flow control is much more challenging [8]. Traditional distribution network is with the features of "passive network" and "one-way power flow," whereas the microgrid is with the features of "active network" and "bidirectional power flow."

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3) Voltage fluctuation and sag often happen in microgrid [9]. In microgrid, except the voltage fluctuation and sags from the load change, most kinds of DERs, which are intermittent and random, will cause significant voltage fluctuations in distribution network.

4) The overvoltage and overcurrent phenomena are more frequent [10]. In general, microgrid is comparatively small in capacity, and the effect of load fluctuation on microgrid is more than that on the traditional power grid. In addition to this, control mode switching of many converters connecting in parallel to bus bar and the seamless state transition may produce overvoltage and overcurrent. So far, relevant research studies on microgrid power quality controllers can be sorted into two types: unifunctional controllers and multifunctional controllers. Unifunctional power quality controllers aim at a specific power quality issue in microgrid. Multifunctional power quality controllers generally combine the power quality controller with the grid interfacing converter through special control scheme [11], [12] or topology [13]. However, these multifunctional power quality controllers do not take into account all of the aforementioned features of microgrid.

To date, there is less research on integrated power quality controller (IPQC) particularly suitable for microgrid with the aforementioned features. In addition, the microgrid capacity is comparatively small, and it is not cost effective to install various types of power quality controller. In order to solve these problems, a novel variable reactor based on magnetic flux control is first proposed. In order to cater for the peculiar requirements of microgrid of harmonic high penetration, frequent voltage fluctuation and overcurrent phenomenon, and bidirectional power flow and small capacity, a novel IPQC suitable for microgrid is proposed based on the novel variable reactor. The IPQC is characterized by mitigating the harmonic penetration, controlling the bidirectional power flow, limiting the fault current and compensating the voltage fluctuation, and being a variable reactor. Finally, simulation results are Provided to validate the analysis.

## II. PRINCIPLE OF THE VARIABLE REACTOR

### 2.1. System Configuration

Fig. 1 shows the single-phase system configuration of the novel variable reactor based on magnetic flux control. Suppose that the turns of primary and secondary winding of the transformer are $N_1$ and $N_2$, respectively. The turns ratio is represented by $k = N_1/N_2$. A transformer with air gap is selected, and its primary winding *AX* can be connected in series or in parallel with power utility. The secondary winding *ax* is not connected with a normal load but a voltage-sourced inverter. The voltages of the primary and secondary windings are $u_1$ and $u_2$, respectively. The primary winding current $i_1$ of the transformer is detected and functions as the reference signal $i_{ref}$ . $h$ is the gain of the current sensor. $U_d$ is the voltage of dc side of the inverter. $C_d$ stands for the capacitance of the dc capacitor. $\alpha$ is a controllable parameter, which will be explained later. The voltage-sourced inverter and the current control are applied to yield a controlled current $i_2$, which has the same frequency as $i_1$. $i_2$ is inversely in phase injected to the Secondary winding *ax*.

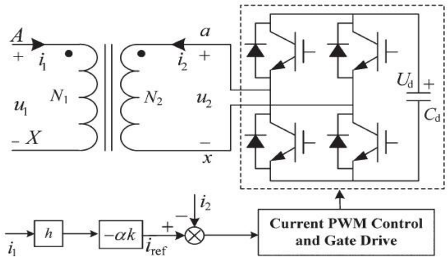


Fig 1: System Configuration of the Novel Variable Reactor

### 2.2. Equivalent T-Circuit of the Transformer

The magnetically coupled circuit of the transformer is central to the operation of the novel variable reactor, which is shown in Fig. 2. The flow of currents in the two windings produces magneto motive forces (MMFs), which, in turn, set up the fluxes.

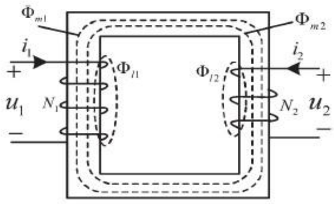

Fig 2: Magnetically Coupled Circuit of the Transformer

The total flux linking each winding may be expressed as

$$\Phi_1 = \Phi_{l1} + \Phi_{m1} + \Phi_{m2} = \Phi_{l1} + \Phi_m \quad (1)$$

$$\Phi_2 = \Phi_{l2} + \Phi_{m2} + \Phi_{m1} = \Phi_{l2} + \Phi_m. \quad (2)$$

Herein, $\Phi_{l1}$ and $\Phi_{l2}$ are the leakage fluxes of the primary and secondary windings. $\Phi_{m1}$ is the magnetizing flux produced by the primary winding, and it links all turns of the primary and secondary windings. $\Phi_{m2}$ is the magnetizing flux produced by the secondary winding, and it links all turns of the primary and secondary windings. $\Phi_m$ denotes the resultant mutual flux.

The voltage equations of the transformer can be expressed as

$$u_1 = r_1 i_1 + d\lambda_1/dt. \quad (3)$$

$$u_2 = r_2 i_2 + d\lambda_2/dt \quad (4)$$

where $r_1$ and $r_2$ are the resistances of the primary and secondary windings, respectively. $\lambda_1$ and $\lambda_2$ are the flux linkages related to the primary and secondary windings, respectively. If saturation is neglected and the system is linear, the following equations can be achieved:

$$\lambda_1 = L_{l1} i_1 + L_{m1}(i_1 + N_2/N_1 i_2) \quad (5)$$

$$\lambda_2 = L_{l2} i_2 + L_{m2}(N_1/N_2 i_1 + i_2) \quad (6)$$

Herein, $L_{l1}$ and $L_{l2}$ are the leakage inductances of the primary and secondary windings, respectively. $L_{m1}$ and $L_{m2}$ are the magnetizing inductances of the primary and secondary windings, respectively. $L_{m1}/N_1^2 = L_{m2}/N_2^2$.when the quantities of the secondary winding are referred to the primary winding, (3) and (4) become

$$u_1 = r_1 i_1 + L_{l1} di_1/dt + L_{m1} d/dt(i_1 + i_2^1) \quad (7)$$

$$u_2^1 = r_2^1 i_2^1 + L1l2di_2^1/dt + L_{m1} d/dt(i_1 + i_2^1) \quad (8)$$

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Here, the prime denotes referred quantities of secondary winding to primary winding. Equations (7) and (8) can be expressed as the following equations in phasor form:

$$U_1 = r_1 I_1 + j\omega L_{l1} I_1 + j\omega L_{m1} (I_1 + I_2^1) \quad (9)$$

$$U_2^1 = r_2^1 I_2^1 + j\omega L_{l2}^1 I_2^1 + j\omega L_{m1} (I_1 + I_2^1) \quad (10)$$

The voltage equations in (9) and (10) with the common $L_{m1}$ suggest the equivalent T-circuit shown in Fig. 3 for the two winding transformer.

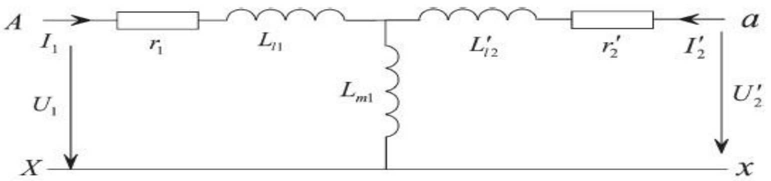


Fig 3: Equivalent T-Circuit of the Transformer

Note that, in some equivalent T-circuit of the transformer, a core loss resistance $r_m$, which accounts for the core loss due to the resultant mutual flux, is connected in parallel or in series with the magnetizing inductance $L_{m1}$ (in the later analysis, a series core loss resistance $r_m$ is taken into account in the equivalent T-circuit of the transformer).

Let $Z_1 = r_1 + j\omega L_{l1}$, which is the leakage impedance of the winding. $Z_2^1 = r_2^1 + j\omega L^1_{l2}$, which is the leakage impedance of the secondary winding *ax* referred to the primary winding. $Z_m = r_m + j\omega L_{m1}$, which is the magnetizing impedance of the transformer. Here, $\omega$ is the fundamental angular frequency. Then, (9) and (10) become

$$U_1 = Z_1 I_1 + Z_m (I_1 + I_2^1) \quad (11)$$

$$U_2^1 = Z_2^1 I_2^1 + Z_m (I_1 + I_2^1) \quad (12)$$

### 2.3. Principle of the Variable Reactor

In Fig. 1, the primary winding current is detected and functions as the reference signal, and the voltage-sourced inverter is applied to track the reference signal to yield a controlled current $i_2$.When controlled current $i_2$ and the primary current $i_1$ satisfy

$$I_2^1 = -\alpha I_1 \text{ (i.e., } I_2 = -\alpha k I_1). \quad (13)$$

Herein, $\alpha$ is a controllable parameter. The transformer is double side energized, and then, the following equations can be obtained :

$$U_1 = Z_1 I_1 + (1 - \alpha) Z_m I_1 \quad (14)$$

$$U_2^1 = Z_2^1 I_2^1 + (1 - 1/\alpha) Z_m I_2^1. \quad (15)$$

In terms of (14), from the terminals *AX*, the equivalent impedance of the transformer can be obtained, i.e.,

$$Z_{AX} = U_1/I_1 = Z_1 + (1 - \alpha) Z_m. \quad (16)$$

In terms of (16), the equivalent impedance of the primary winding of the transformer is a function of the controllable parameter $\alpha$. When $\alpha$ is adjusted, the primary winding exhibits consecutively adjustable impedance. Equation (16) can be also achieved in terms of the resultant MMFs of the two windings acting around the same path of the core. When a controlled current $i_2$ produced by a voltage sourced inverter is injected into the secondary winding of the transformer and $i_2 = -\alpha k i_1$, the resultant MMF is $N_1 I_1 + N_2 I_2 = (1 - \alpha) N_1 I_1$. Then, the resultant flux set up by the MMF of the two windings is $(1 - \alpha)\,\Phi_m$. Then, the induced voltage produced by the resultant flux can be expressed in phasor form as

$$E_1 = (1 - \alpha)\, j\omega L_m I. \quad (17)$$

The primary voltage equation can be achieved as (14).In terms of (16), the relation between the equivalent impedance of the primary winding and the parameter $\alpha$ is shown in Table I.

| $\alpha$ | The equivalent impedance of terminal $AX$ | Impedance charateristic |
|---|---|---|
| $\alpha < 0$ | $Z_{AX} > Z_1 + Z_m$ | resistive and inductive |
| $\alpha = 0$ | $Z_{AX} = Z_1 + Z_m$ | |
| $0 < \alpha < 1$ | $Z_1 < Z_{AX} < Z_1 + Z_m$ | |
| $\alpha = 1$ | $Z_{AX} = Z_1$ | |
| $1 < \alpha < 1 + Z_1 / Z_m$ | $Z_1 < Z_{AX} < 0$ | |
| $\alpha = 1 + Z_1 / Z_m$ | $Z_{AX} = 0$ | 0 |
| $\alpha > 1 + Z_1 / Z_m$ | $Z_{AX} < 0$ | resistive and capacitive |

Table 1 : Equivalent Impedance of the Primary Winding of the Transformer

The variable reactor features hardly producing harmonics, simple control scenario, and with consecutive adjustable impedance. Many flexible ac transmission systems (FACTS) devices can be implemented in terms of the novel principle [38]. The variable reactor can be used in unified power flow controller to change the line impedance between the sending and receiving ends to control the power flow; it can also substitute the thyristor-controlled reactor of the thyristor-controlled series capacitor; however, the proposed variable reactor does not produce any harmonics; fault current limiter can be also implemented. In terms of the novel principle of the variable reactor. Reactive power compensation can be all realized by the novel variable reactor. In addition, it has been successfully applied the hybrid series active power filter based on fundamental magnetic flux compensation.

### 2.4. DC-Link Voltage Control of the Variable Reactor

There must be some losses when the novel variable reactor system with inverter operates normally, and the inverter will absorb active power to maintain the dc voltage constant. Fig.4 shows the dc-link voltage control schematic of the variable reactor system. Herein, $U_d{}^*$ and $U_d$ represent the inverter dc reference and practical voltage, respectively. An active current reference $i_p$ is added to the reference signal $i_{ref1}$ to achieve a new reference signal $i_{ref2}$. A dc-link voltage PI controller is applied to make the inverter dc practical voltage $U_d$ follow the dc reference voltage $U_d^*$. The output of the voltage PI controller is multiplied by the phase-locked loop (PLL) output of $u_2$ to yield the active current reference $i_p$.

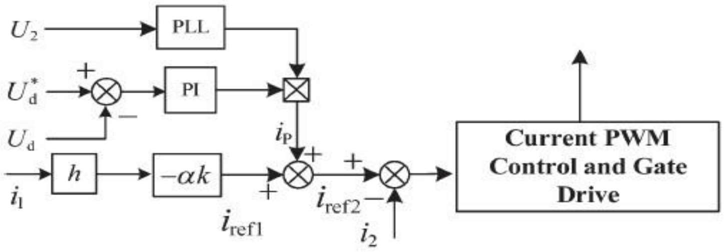


Fig 4: DC Link Voltage Control Schemati

## III. PRINCIPLE OF THE IPQC

### 3.1. System Configuration

The novel IPQC can be installed in series and parallel in microgrid or point of common coupling (PCC). For simplicity, the IPQC is installed in PCC. Fig.5 shows the three-phase detailed system configuration of the IPQC with transformer and inverter. $U_s$ and $L_s$ represent the source voltage and impedance of conventional power supply, respectively. The passive filters, which have the function of absorbing the harmonics, are shunted in both sides. The primary winding of a transformer is inserted in series between the conventional power utility and the micro grid, whereas the secondary winding is connected with a voltage-source PWM converter. $U_d$ is the voltage of the dc side of the inverter. The micro grid contains a harmonic load, a photovoltaic cell system, a battery storage system, and a normal load. The proposed IPQC has the following functions.

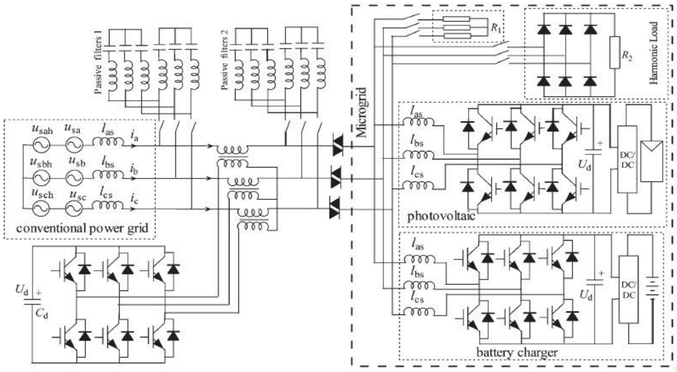


Fig 5: Circuit of Proposed IPQC

### 3.2. Power Flow Control

When the power flow control and the fault current limiter are of concern, only the fundamental is taken into account. In terms of the preceding analysis, the primary winding exhibits adjustable impedance $Z_1 + (1 - \alpha) Z_{m.}$ With the change in coefficient $\alpha$, the equivalent impedance of the primary winding can be achieved, which is shown in Table I. Therefore, when the primary winding is connected in series in circuit, it can be applied to control the power flow between the conventional power utility and the microgrid or the internal power flow of the microgrid. The schematic of power flow control is shown in Fig. 6 when the novel variable reactor is connected in series between the sending and receiving ends. Suppose that the equivalent impedance $Z1 + (1 - \alpha)$ $Zm$ of the variable reactor is $R + jX$. In terms of the vector diagram in Fig. 6, the following equations can be obtained:

$$Um \cos \phi = Us \cos(\phi - \delta) + RI \tag{21}$$

$$Um \sin \phi = Us \sin(\phi - \delta) + XI. \tag{22}$$

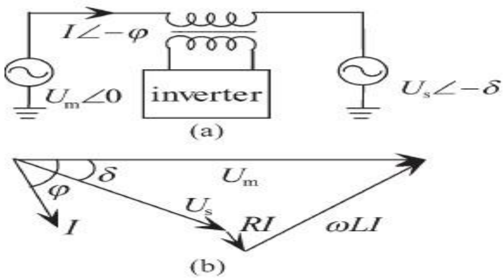


Fig 6: Power Flow Control Principle and Its Vector Diagram

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Multiply cos $\phi$ in both sides of (21) and multiply sin $\phi$ in both sides of (22), then the following equation can be obtained by adding them:

$$U_m (U_m - U_s \cos\delta) = PR + QX. \quad (23)$$

Multiply sin $\phi$ in both sides of (21) and multiply cos $\phi$ in both sides of (22), then the following equation can be obtained by subtracting them:

$$U_s \sin\delta = PX - QR. \quad (24)$$

In terms of (23) and (24), the active and reactive power from $U_m$ to $U_s$ is

$$P = \frac{Um}{R2 + X2}[R(U_m - U_s \cos\delta) + XU_s \sin\delta] \quad (25)$$

$$Q = \frac{Um}{R2 + X2}[-RU_s \sin\delta + X(Um - U_s \cos\delta)] \quad (26)$$

In the power system with high voltage level, the inductive reactance component of the transmission line is much more than the resistance component of the transmission line, (25) and (26) become

$$P = UsUm/X \sin\delta \qquad Q = Um/X\,(Um - Us \cos\delta) \quad (27)$$

In microgrid with low voltage level, when the resistance component of the transmission line is much more than the

Inductive reactance component of the transmission line, (25) and (26) can be expressed as

$$P = Um/R(Um - Us \cos\delta)\ \ Q = -UmUs/R \sin\delta \quad (28)$$

In terms of (28), there is a striking difference in power flow control and voltage regulation between microgrid and

Conventional power grid.

### 3.3. Fault Current Limiter

When the terminal *AX* is connected in series in circuit, in the normal operation state, the coefficient $\alpha$ can be controlled as $\alpha = 1+Z1/Zm$, and the equivalent impedance of the primary winding *AX* is zero. Hence, the series transformer does not have any influence on the power system normal operation. The maximum system current $I_{smax}$ of the three phases is obtained by a current-detecting circuit and compared with a reference current. In case of a short-circuit fault, maximum system current $I_{smax}$ reaches the reference current, the coefficient $\alpha$ can be controlled between −1 and 1 in terms of the requirement of fault current, and the equivalent impedance of the primary winding *AX* is controlled between $Z_1 + Z_m$ and $Z_1$ to limit the system current to a desired value.

### 3.4. Voltage Compensation

In order to compensate the voltage fluctuation, the primary winding of the transformer is connected in series between the power electric utility and the load. When the load voltage is higher than the desired voltage, the coefficient $\alpha$ can be controlled between 0 and $1 + Z_1/Z_m$, and the primary winding exhibits inductive impedance. When the load voltage is lower than the desired voltage, the coefficient $\alpha$ is controlled more than $1 + Z_1/Z_m$, and the primary winding exhibits capacitive impedance. Therefore, the load voltage can be controlled as a stable voltage.

### 3.5. Harmonic Isolation

The preceding function of power flow control, fault current limiter, and voltage compensation is concerned with the fundamental. If there exits harmonic in the power utility, the primary current contains the fundamental current and *n*th order harmonic currents, that is to say, $i_1 = i_1^{(1)} + \sum i_1^{(n)}$. The fundamental component $i_1^{(1)}$ rather

International Journal of Advanced Technology in Engineering and Science
Vol. No.4, Issue No. 10, October 2016
www.ijates.com
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than harmonic is detected from the primary winding current $i_1$ and functions as a reference signal. A voltage source inverter is applied to track the fundamental reference signal $i_1^{(1)}$ to produce a fundamental compensation current $i_2^{(1)}$ which has the same frequency as $i_1^{(1)}$. $i_2^{(1)}$ is inversely in phase injected to the secondary winding *ax*. When $\alpha$=1+$Z_1/Z_m$, the fundamental equivalent impedance of primary winding *AX* is zero. Meanwhile, for the *n*th-order harmonic, since only a fundamental current is injected to the secondary winding of the transformer, *i*2 does not include any order harmonic current other than the fundamental current, which means that the transformer is open circuit to harmonic current. Then, the harmonic equivalent impedance of the transformer is

$Z_{AX}^{(n)} = (r1 + jnx1) + jnx_m \approx nZ_m^{(1)}$

From the primary winding, the series transformer exhibits very low impedance at the fundamental and simultaneously exhibits high impedance to harmonics to act as a "harmonic isolator." Then, the harmonic currents are forced to flow into the passive *LC* filter branches in both sides.

### 3.6. Ipqc

When integrating the preceding functions of variable reactor, power flow control, fault current limiter, voltage compensation, and harmonic isolation, a novel IPQC can be achieved. For fundamental and harmonic, the primary winding of the series transformer exhibits the impedance of $Z_1^{(1)} + (1 - \alpha)Z_m^{(1)}$ and $nZ_m^{(1)}$ , respectively. That is to say, the primary winding of the series transformer exhibits adjustable impedance, which plays the role of power flow control, fault current limiter, and voltage compensation to fundamental. Meanwhile, the primary winding of the series transformer exhibits high impedance $nZ_m^{(1)}$ to harmonic, which can greatly improve the source impedance to harmonics, and really acts as a harmonic isolator. Therefore, it can mitigate the harmonic high penetration.

## IV. CONTROL SYSTEM

We have three cases here, in first case principle of variable reactor is verified, it means in place of microgrid we employ two switches of impedance Z1 and Z2. Fig 8 record the transient current and voltage waveforms of the primary winding when α changes from 0.1 to 0.6 and from 0.6 to 1.In case-2 harmonic high penetration is verified, here harmonics are injected at the supply side and a breaker is arranged with a timer of 1 minute and it shows how harmonics are mitigated at supply side by using IPQC. In case-3 also harmonic high penetration is verified, here harmonics are injected at the load side and a breaker is arranged with a timer of 1 minute and it shows how harmonics are mitigated at load side by using IPQC.

| **Parameter** | **Value** |
|---|---|
| Ratio of series transformer | 1:1 |
| Magnetizing impedance Zm | 16.309 ohm |
| Leakage impedance Z1 | 0.088 ohm |
| System voltage | 172V |
| DC voltage of DC capacitor | 150V |

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| | |
|---|---|
| Passive filters (L3) | 28.17mH |
| Capacitor(C3) | 40 uF |
| Capacitor(C5) | 20 uF |
| Inductor(L5) | 20.28 mH |

Table 2: System Parameters and Its Values

## V. RESULTS

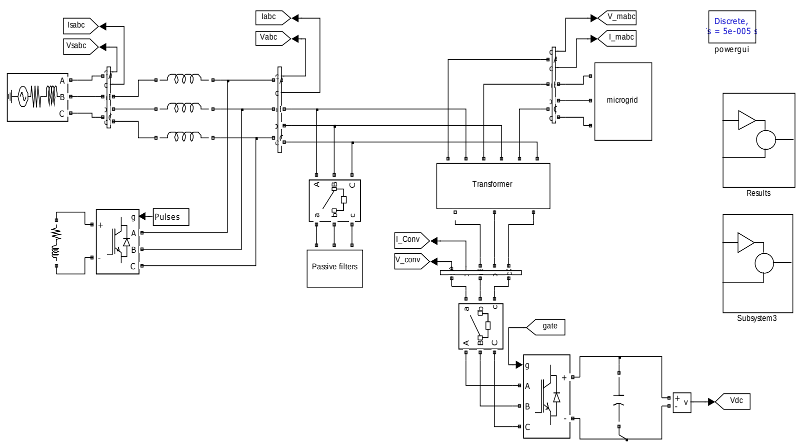


Fig 7: Simulation circuit to verify principle of variable reactor, harmonic isolation

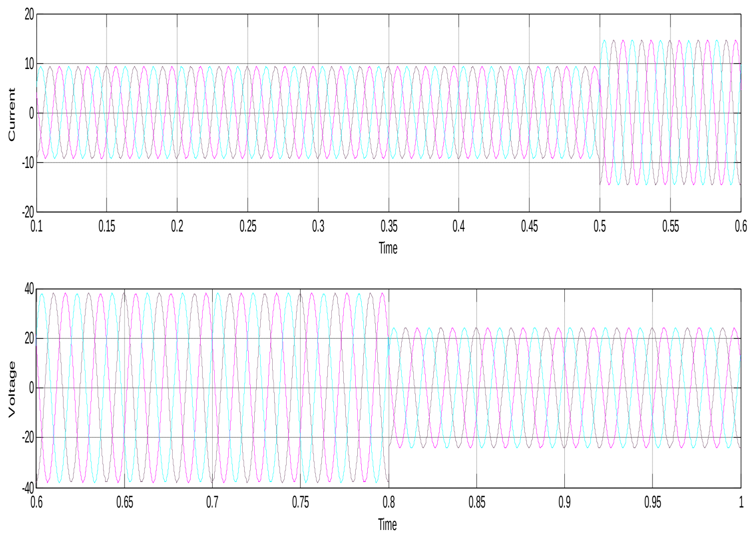


Fig 8 :Current and voltage waveforms of the primary winding when α suddenly changes from 0.1 to 0.6 and 0..6 to 1

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Vol. No.4, Issue No. 10, October 2016
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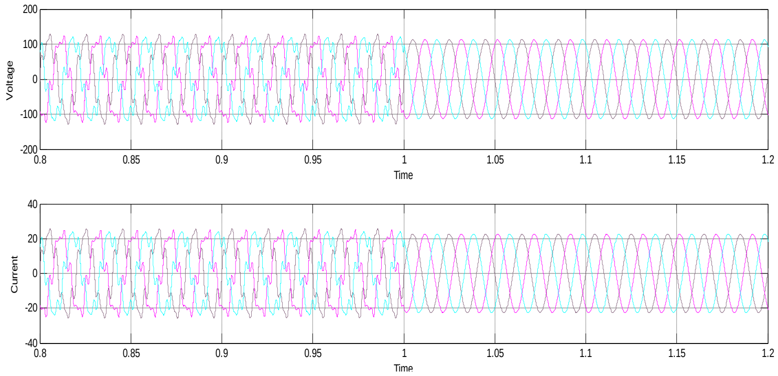


Fig 9 : Simulation waveforms when IPQC is not employed and after breaker applied and IPQC employed in case-2

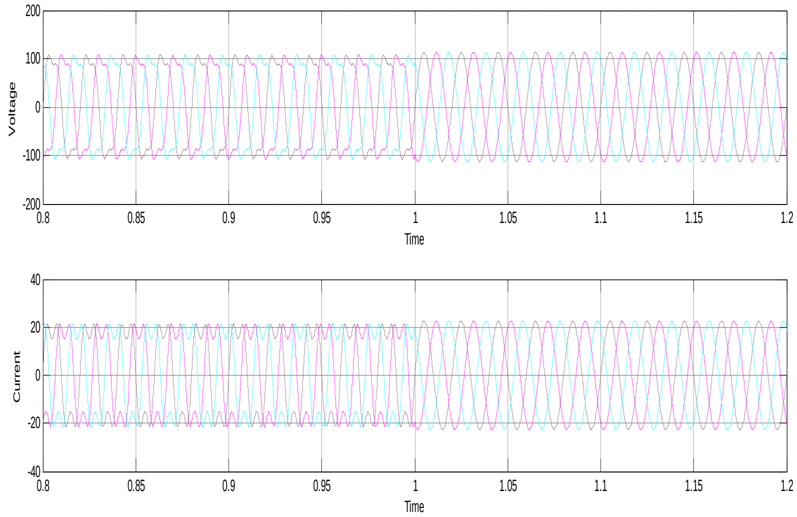


Fig 10: Simulation waveforms when IPQC is not employed and after breaker applied and IPQC employed in case-3

## VI. CONCLUSION

This paper presents a novel variable reactor based on the magnetic flux control. A transformer with air gap is selected, and the primary winding current of the transformer is detected. A voltage-sourced inverter is applied to follow the primary current to produce another current, which is injected to the secondary. When the injected current is adjusted, the equivalent impedance of the primary winding of the transformer will change continuously. The variable reactor features hardly producing harmonics, simple control scenario, and with consecutive adjustable impedance. The ramp comparison current control with PI controller, which is suitable for DSP microcontroller, is chosen as control current. In terms of the novel variable reactor, a novel IPQC suitable for microgrid is proposed. The primary winding exhibits adjustable impedance, which plays the role of power flow control, fault current limiter, and voltage compensation to fundamental. Meanwhile, the primary winding exhibits high impedance to harmonic, which can greatly improve the source impedance to harmonics, and really acts as a harmonic isolator. Therefore, it can mitigate the harmonic high penetration.

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