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Islanding Detection and Stability Improvement of DG by Using Inverter Control Scheme



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Abstract:

The design of inverter controller is to improve both system stability and islanding detection performance with the Non Detection Zone (NDZ). The islanding operation for DG system can cause a number of negative impacts on a microgrid and the DG system itself, such as safety hazards, power quality problems, and serious damage to the system unless the main utility power is restored correctly and quickly. To solve these problems, several recent researchers have developed two types of islanding detection methods (IDMs) with high-performance. One is the power and voltage (P-V) characteristic of load based IDM, and the other is the inverter's switching frequency based IDM. The proposed controller uses the magnitude and phase of measured voltage directly instead of Park's transformation. It does not need an instant phase of point of common coupling (PCC) voltage, which is required in the conventional controller.In the viewpoint of protection, the proposed controller provided the better islanding detection performance than the conventional controller by reducing the detection time. The simulation results shows the effectiveness of the proposed controller has better performance than the convention controller.

Key words:
Distributed generation (DG), inverter controlalgorithm, islanding detection, phase-locked loop (PLL) independent control, stability.

I.INTRODUCTION:

IN response to increase of electric power consumption, theelectric power industry is trying to address numerous chal-lenges such as generation diversification, optimal deployment of expensive assets, demand response, energy conservation, and reduction of the industry's overall carbon footprint . As the existing electric power grid cannot deal with these critical is-sues, the next generation technology of smart grid, which is the well-planned plug-and-play integration of smart microgrids, is being studied worldwide.In contrast to conventional power system, the smart grid consists of various distributed generation (DG) systems as well as huge power plants. The DG systems are applied to derive the maximum utilization of existing infrastructures by increasing system stability and reducing transmission loss. Moreover, it is expected to provide the proper solution to handle the rapid increase of power consumption with the short construction time, high compatibility based on renewable energy resources, and quick response to the peak load demand. All components including the DGs and customer loads must be Integrated and controlled in an effective manner.

However, its Implementation is not easy in practice because it requires not only the development of component itself, but also their appropriate management and control. However, the growth of DG systems is rapidly progressing, and they are being connected to power grids worldwide. Then, it is required to design its proper controller to improve the stability and reliability of system. On the other hand, the islanding operation for DG system can cause a number of negative impacts on a microgrid and the DG system itself, such as safety hazards, power quality prob-lems, and serious damage to the system unless the main utility power is restored correctly and quickly.To solve these problems, several islanding detection methods (IDMs) without non -detection zone (NDZ) have been recently developed .

One is the power and voltage (P-V) characteristic of load based IDM, and the other is the inverter's switching frequency based IDM . Although the above methods have no NDZ, their usefulness mainly depends on the control performance of the inverter in practice. In other words, the inverter used in DG system must achieve the decoupled real and reactive control and successful operation of the phase-locked loop (PLL). The conventional controller of inverter has been designed by using the Park's transformation. Then, it is able to control the real and reactive powers with the assumption that they are ideally decoupled. However, they are not completely decoupled in practice, and their mutual dependence becomes strong in the case that the PLL performs poorly. This paper pro-poses the design of the inverter controller, which operates independently of the performance of the PLL, while it still provides zero NDZ property.

Moreover, the proposed inverter controller is easy to implement because it uses only two proportional-integral (PI) controllers while the conventional controllers normally uses four.

II.ISLANDING DETECTION METHODS:

A. Distributed Generation System:

The DG system is usually connected to the distribution net-work where many customers consume large amount of power . However, these benefits are only effective when they are correctly operated. Then, the islanding detection is one of the most important issues to achieve these beneficial effects. As shown in Fig. 1, the DG system is connected to a part of real distribution network of 60MVA-scale, which is located at the Do- gok area in Seoul, Korea.

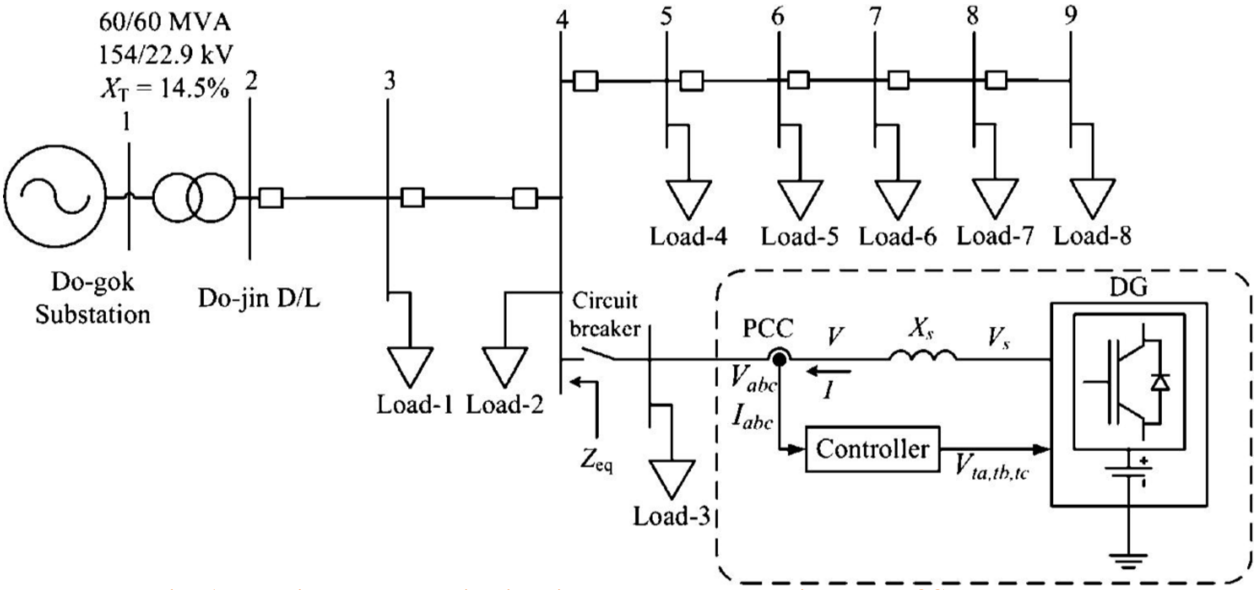

Fig. 1.Practical Do-gok distribution power network ina partof Seoul, Korea.

The DG system supplies power by injecting current while the terminal voltage is synchronized with the voltage on the point of common coupling (PCC). The inverter controller in Fig. 1 uses the measured voltage and/or current data to control its output power. However, they are not completely decoupled in practice, and their independence mainly depends on the controller's performance and successful operation of the PLL. More details for this issue are described in Section III.

B.Inverter's Switching Frequency Based IDM:

When the circuit breaker in Fig. 1 is open, the islanding op-eration occurs if the DG system supplies the power continuously.

Then, the equivalent impedance referring to the side of DG is changed rapidly. The difference in impedances before and after the islanding operation becomes larger when the frequency increases. In general, the pulse-width modulation (PWM) inverter is used for the DG system, and it has two representative frequency components of voltage output. The fundamental component may stay inside the NDZ if the equivalent impedances before and after the islanding operation are the same. In this case, the conventional passive and active IDMs may fail to detect the islanding operation.In contrast, the inverter's switching frequency based islanding detection method (SFIDM) in operates correctly without the NDZ. For more details of SFIDM, the reader would refer to.

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C. P-V Characteristic of Load Based IDM:

Differently from the conventional OUV/OUF IDM, the-Power and voltage (P-V) characteristic of load based IDM(PVIDM) in [9] changes the output power, Pinv of inverter according to the magnitude of voltage, V to improve the islanding detection performance. If the Pinv is controlled by (1),the NDZ is reduced by comparing to the case of constant Pinv :

$$P_{inv}=0.5.V+0.5, \qquad (1)$$

Also, if the Pinv is controlled by (2), the NDZ can be more reduced. Actually, the NDZ is eliminated if the slope of P-V characteristic is equal to or larger than 2 (for more details of PVIDM, the reader would refer to [9]):

$$P_{in}v=2.V-1, \qquad (2)$$

III. DESIGN OF PROPOSED INVERTER CONTROLLER:

A.Conventional Inverter Controller:

The inverter based DG system has a great ability to maintain the unit power factor by controlling the reactive power to be zero. Its conventional controller has been designed to operate the real and reactive powers independently by adjusting the decoupled direct and quadrature (d-q) axes currents, Idand I qbased on the Park's transformation . In a balanced three-phase system, the instantaneous phase voltages are represented with a sinusoidal form as (3)–(5):

$$V_a= V_{peak}Cos(\omega t+\delta v) \qquad (3)$$
$$V_b= V_{peak}Cos(\omega t +\delta v - 2\pi/3) \qquad (4)$$
$$V_c = V_{peak}Cos(\omega t + \delta v + 2\pi/3) \qquad (5)$$

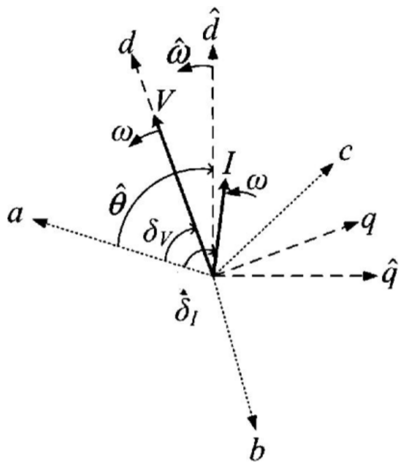

Fig. 2.Phasor diagram to describe the Park's transformation.

Where Vpeak , ω , and δV denote the peak voltage, frequency, and initial phase of Va , respectively. In this paper, thecounterclockwise direction is defined to be positive angle as general. Then, the phasor diagram for the voltages is shown in Fig. 2, where the relationship between a-b-c phases and d-q phases is represented.

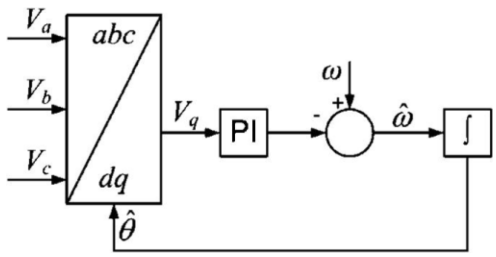

Fig. 3. Block diagram of phase-locked loop (PLL).

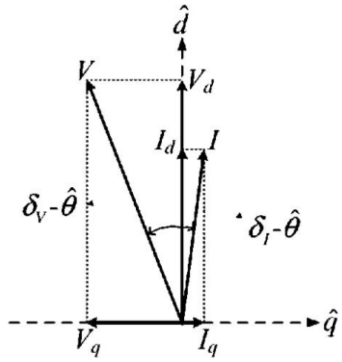

Fig. 4.Phasor diagram to describe the Park's transformation when the PLL is not ideal.

When the PLL in Fig. 3 is ideally operated to make its q-axis component to be zero, the voltage, V is placed on the same line as the d-axis. as shown in Fig. 3, which make the response to be lagging. Therefore, the estimated direct and quadrature axes, which are d – q axes in Fig. 2, become different from the original d – q axes even though the PLL performs effectively.The parameter, θ, denotes the initial angle from the a-axis tothe estimated -axis. Then, the d – q axes components for V and I are shown in Fig.4. The voltage and current outputs fromPark's transformationhave non-zero values in their q axis component, and they arecomputed by (6) and (7):

$$V_d = V_{peak}Cos((\omega-\acute{\omega})t + \delta v – \theta)$$
$$I_d =I_{peak} Cos((\omega-\acute{\omega})t + \delta I– \theta) \qquad (6)$$
$$V_q = V_{peak}Sin(\omega - \acute{\omega})t + \delta v – \theta)$$
$$I_q= I_{peak}Sin(\omega - \acute{\omega})t + \delta I – \theta) \qquad (7)$$

Where I_{peak} is the peak value of Iin Figs. 2 and 4.Thereafter, the real and reactive powers are determined with the V_d, V_q, I_d and I_q in (6) and (7), and they areexpressed by(8) and (9),respectively:

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$$P = \frac{3}{2}(V_d \cdot I_d + V_q \cdot I_q) \quad (8)$$

$$Q = \frac{3}{2}(V_d \cdot I_q - V_q \cdot I_d). \quad (9)$$

For example, the value of component is zero when d-axis issynchronized to and therefore d-axis becomes same as axis in Fig. 2. Then, (8) and (9) can be expressed as (10) and (11), respectively:

$$P = \frac{3}{2} V_d \cdot I_d \quad (10)$$

$$Q = \frac{3}{2} V_d \cdot I_q. \quad (11)$$

Based on the above assumption that they can be controlled in-dependently, the conventional inverter controller [12]–[16] has been designed as shown in Fig. 5. Then, it is compared with the actual d-axis current component, Id in (10). The controller, PI2 generates the signal to control the d-axis source voltage component, Vsd. It increases when the value of Id is smaller than that of Idref. The other voltage component, IqώLs, is calculated with the measured Iq, where Ls is the inductance that forms the impedance, Xs(= Rs + jωLs) in Fig. 1. Also, the q-axis source voltage component, Vsq, is controlled by the controllers, PI3 with PI4 in the same manner. Even though the and can be controlled independently as given in (10) and (11), they might be actually decoupled in a transient response because the internal PI controllers in Fig. 5 have their finite response time. For example, when the value of Id which is different from that of Idref during short transient period, is decreased, this causes to change in values of signals, Vad and Vsq. Then, both P and Q are affected in this transient period by the conventional controller even if the PLL is ideal, and therefore the P and Q are perfectly independent in a steady state condition. The PLL has an important role in the use of synchronous reference frame based on the Park's transformation since it makes the outputs, Vd, Vq, Id and Iq to be constant in a steady state. Also, it is implemented so that it can make Vq to be zero as shown in Fig. 3. However, if these functions of PLL do not work perfectly, then the reference phase angle does not properly synchronized with that of PCC voltage. This results in Vd, Vq, Id and Iq with many ripples, and therefore the control performance of inverter by adjusting the and Iq will be degraded. In addition, the P and Q cannot be controlled independently because is not zero any more. In practice, the PLL never operates ideally as mentioned in above. Thus, the conventional inverter controllers designed under the assumption that the P and Q are ideally decoupled, have the limitations in their control actions

B. Design of Proposed Inverter Controller:

The proposed inverter controller is designed to operate without the PLL and improve the power system stability and islanding detection performance. Its control block diagram is shown in Fig. 6.

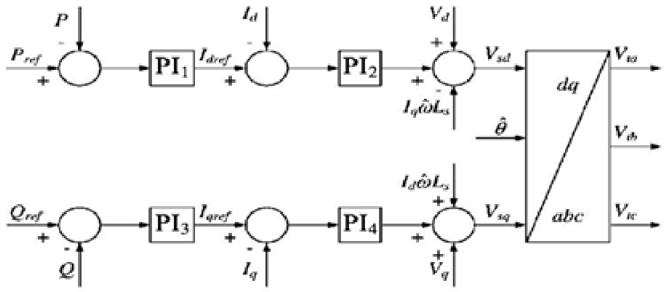

Fig. 5. Block diagram of conventional inverter controller.

In Fig. 6, the proposed controller has the "phase-shifter", which is the main part of controller. It performs based on the Park's transformation by the angle, θref and the inverse Park's transformation by the angle, θ'ref, which is compensated with the output signal, θ, from the PI controller for reactive power (θ'ref = θref_ θ). Note that any arbitrary value of θref can be used even though it is a time-varying parameter. It is because the θref never have any effect on the phase difference between and V'. Therefore, the proposed controller does not require any devices to determine the specific phase value. Its detailed operation is explained with the phasor diagram illustrated in Fig. 7.Initially, the Park's transformation is computed with the angle, θref , for the d - q axes without regard to its constant or time varying values. Note that the d-axis is lagging the a-axis by the θref. The Vd and Vq are the voltages on the d and q axes, respectively. Then, their numerical values are transferred from the Park's transformation to the inverse Park's transformation blocks, as shown in Fig. 6. These transferred values are used for the voltages, V'd and V'q . Because the d'-axis is lagging the a-axis by the θ'ref, the inverse Park's transformation is calculated with the new angle, θ'ref , for the changed d' and q' axes. Consequently, the transfer from the d_q axes to the d'_ q' axes makes the phase of voltage to be shifted. This phase shift corresponds to the angle, θ, as shown in Fig. 7. Therefore, according to the new reference angle, θ'ref = θref_ θ , the phaseof output voltage, V' is shifted by the angle of- θ from that of input voltage, V. In other words, V' leads V.

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Thereafter, the magnitudes of voltages (V'a, V'b, and V'c) from phase-shifter are multiplied by the output signal, Vmag, of PI controller for active power. Then, each a-b-c phase component of Vmag. V' determines the output voltage reference signals (Vta, Vtb and Vtc) after summing up with the corresponding measured voltages (Va, Vb and Vc), as shown in Fig. 6. It is observed from the dashed-line box in Fig. 1 that the difference between PCC voltage, V, and inverter output voltage, v0, is the voltage drop, Vfilter, across the filter, Xs. This relationship of Vfilter = V0_V is also explained with the phasor diagram in Fig. 8. For the inverter control, Vt in Fig. 6.

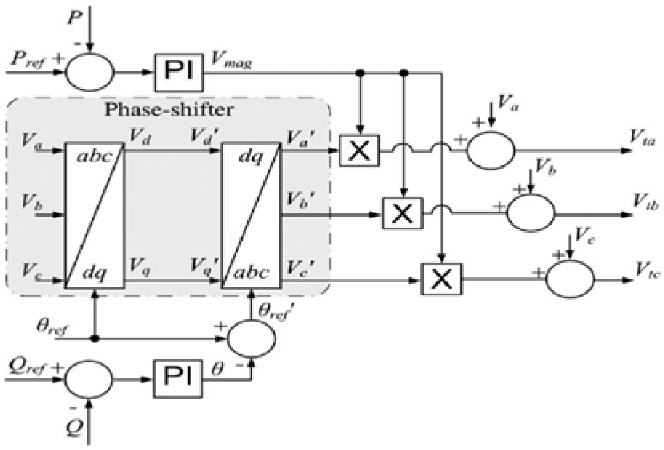

Fig. 6. Block diagram of proposed inverter controller by using magnitude and phase angle of voltage.

where the current, I, can be directly controlled by adjusting Vfilter because the fixed impedance of the filter, Xs, makes the phase angle, φ (= tan-1(L0/R0)), in Fig. 8 to be constant, and the magnitude of is proportional to that of Vfilter. Finally, the P is controlled by the linear relationship with the I, and Q the is relatedwith the value of θ. For example, the θ decreases when the actual reactive power, Q becomes larger than its reference, Qref (see Fig. 6). This means that Vfilter and I in Fig. 8 rotate to counterclockwise direction by the decreased θ, and the Q decreases correspondingly.Because Vmag, V' and Vfilter have physically same values, and ' has the same magnitude with , the magnitude of current, I can be expressed as (12):

$$(12) \quad I| = \frac{V_{filter}}{|X_s|} = \frac{V'|}{|X_s|} \cdot V_{mag} = \frac{V|}{|X_s|} \cdot V_{mag}.$$

Then, (13) and (14) can be derived from the p has or diagram in Fig. 8 describing how the proposed method controls the output powers of inverter:

$$P = |V| \cdot |I \cos(\varphi - \theta) = \frac{V|^2}{|X_s|} \cos(\varphi - \theta) V_{mag} \qquad (13)$$

$$Q = |V \cdot I| \sin(\varphi \quad \theta) = \frac{V|^2}{|X_s|} \sin(\varphi \quad \theta) V_{mag}. \qquad (14)$$

Finally, (15)–(18) are derived from (13)–(14):

$\delta P/\delta\theta = V^2/X_s \, \mathrm{Sin}(\varphi - \theta) V_{mag}$ (15)
$\delta P/\delta_{Vmag} = V^2/X_s \, \mathrm{Cos}(\varphi - \theta)$ (16)
$\delta Q/\delta\theta = -V^2/X_s \, \mathrm{Cos}(\varphi - \theta) V_{mag}$ (17)
$\delta Q/\delta V_{mag} = V^2/X_s \, \mathrm{Cos}(\varphi - \theta)$. (18)

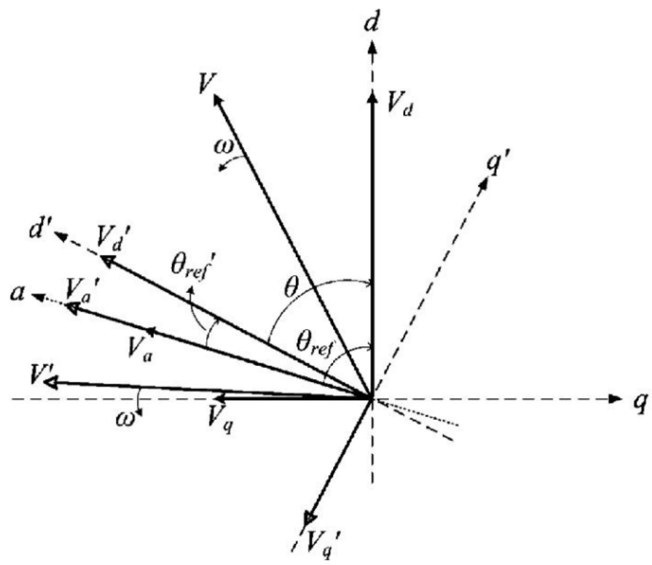

Fig. 7.Phasor diagram to describe the operation of phase-shifter in the pro-posed controller.

In (15), the P becomes insensitive to the change of phase angle, θ, if φ – θ is zero. Then, it is associated with the only change of Vmag by (16). In contrast, the Q responses linearly to the (negative) change of phase angle, θ, when φ – θ is zero by (17). Also, the Q is insensitive to the change of Vmag by (18).Note that the proposed controller in Fig. 6 does not require the additional PI2 and PI4 of conventional controller in Fig. 5 to control the output power by (10) and (11). This improves the performance of proposed controller and makes it easier to determine the proper PI parameters in use. Also, the desirable power factor is greater than 0.95 in practice. In this condition, the P is almost insensitive to the change of phase angle, θ, because the angle between V and I, which is φ – θ in Fig. 8, is very small. In the same manner, the Q is hardly changed by the Vmag control. In other words, the P and Q are controlled in thealmostdecoupled mode by the proposed controller when the powerfactor is close to be unity.

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Moreover, the proposed controllerdoes not use the PLL, and therefore it does not affected by theperformance of PLL like the conventional controller. Considerthat the P and Q are 1 pu and 0 pu, respectively, and the performanceof PLL is not satisfied. The conventional controller cannot control both powers independently because Vq and Vd vary in any operating conditions. For example, in an operating mode of Vq =Vd =0.866pu and Iq = Id= 0.577 pu,(10) and (11) cannot be applied because Vq is not zero in thiscase. In other words, the fundamental theory used in the designof conventional controller is not valid any more, and it mightfail to control the inverter. In contrast, the proposed controllercan control it successfully. In addition, the proposed controllereasily synchronizes the DG output to the grid because it uses the three-phase grid voltages, Va, Vb, and Vc, as shown in Fig. 6.

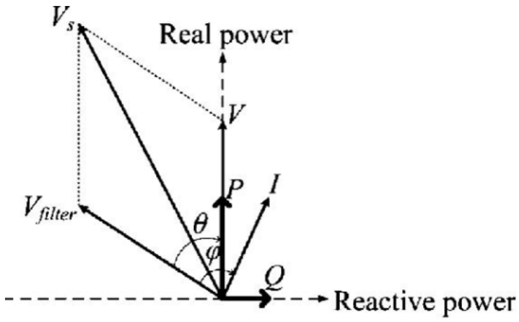

Fig. 8.Phasor diagram to describe the relationship among Vfilter, Vs and V.

IV. CASE STUDIES FOR INVERTER CONTROL:

A. Case with Different:

It is mentioned in Section III-B that the proposed inverter controller operates successfully without the PLL by reference angle for the Park's transformation. To verify thisperformance, a time-domain simulation based case study is carried out by the power systems computer aided design/electromagnetic transients including DC (PSCAD/EMTDC®) software.

The result is shown in Fig. 9. the actual real and reactive powers of system correspond to the synchronized θref(= ωt). It is observed from the result that the proposed controller operates consistently without regard to the value of θref.

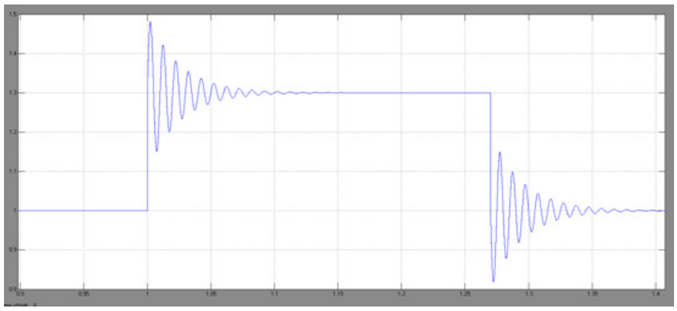

Fig 9.1 Real Power(P) synchronized Performance (θref =wt)

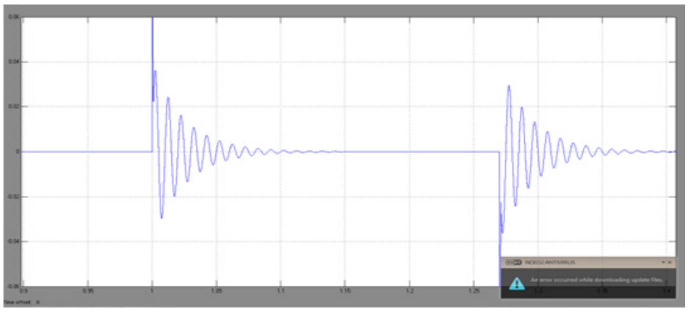

Fig 9.2Reactive Power(Q) synchronized Performance (θref =wt)

B. Case with Start of Inverter:

The size of DG should be determined with the careful considerations for its location, protective coordination, amount of load consumption, and power quality, etc to improve the stability and reliability of system . In particular, the amount of load consumption always varies, and thus the inverter is required to produce the corresponding real power. In addition, it should be able to regulate the reactive power because the stability is strongly affected by its variations. Therefore, the DG can operate to supply the peak load demand effectively even if there are sudden variations in the input driver. When the inverter starts tooperate, the dynamic performances of the conventional and proposed controllers are compared in Fig. 10.

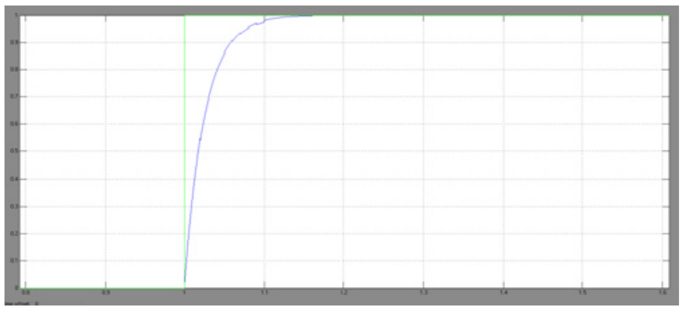

Fig 10.1 Real Power(P) Proposed Inverter starting Response

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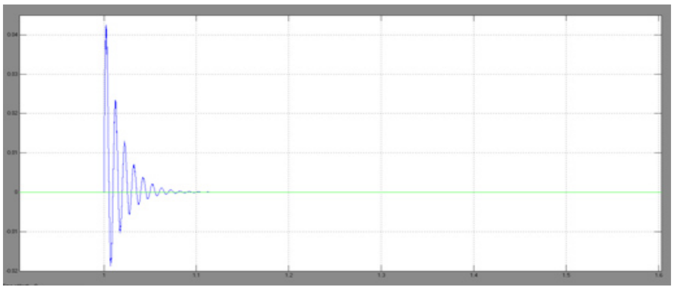

Fig 10.2 Reactive Power(Q) Proposed Inverter startingResponse

C. Case With Changed Pref and Qref is Zero & Non Zero(0.31pu):

In general, the inverter should make the reactive power to be zero for the unit power factor. For this case, the performances of controllers are evaluated with the changes Pref in for load variations and zero Qref. The result is shown in Fig. 11

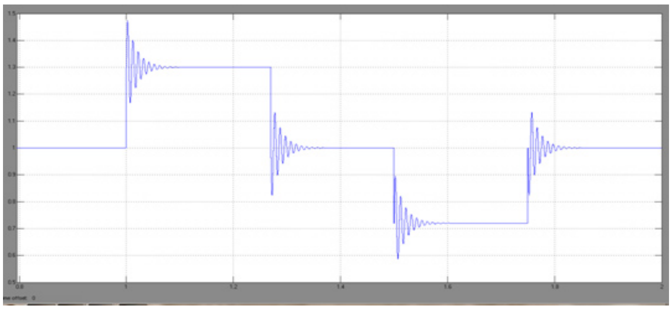

Fig 11.1Real Power(P) Proposed Inverter Changed performance

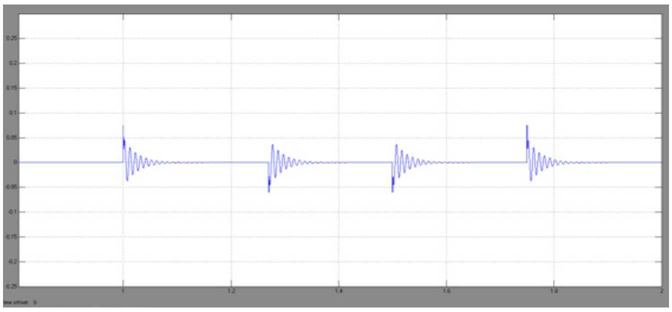

Fig 11.2Reactive Power(Q) Proposed Inverter Zero Performance

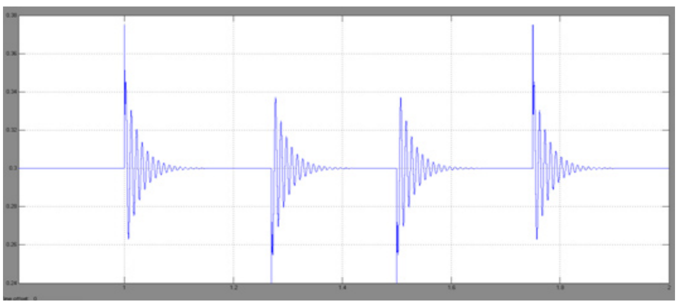

Fig 11.3 Reactive Power Proposed Inverter Non-Zero(Qref =0.31 pu)Performance

V. CASE STUDIES FOR ISLANDING DETECTION:

A. Case with Different Load Consumption and DG Output:

when the load consumption is larger than 1.29 pu or less than 0.82 pu [9]. For this case, the amount of loads is set to be 1.3 pu and 0.8 pu corresponding to under and over voltage limits, respectively,The results by the OUV method are shown in Fig.12

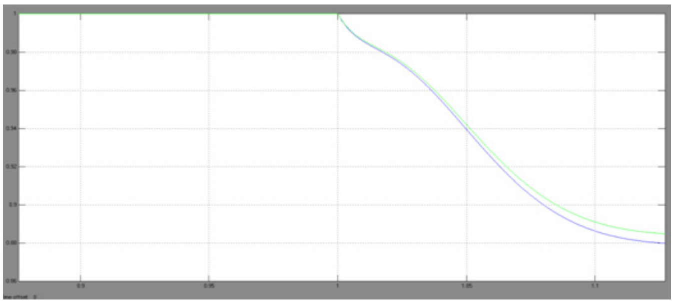

Fig.12.1Vrms pu Signal Performance when Pload=1.3Pinv

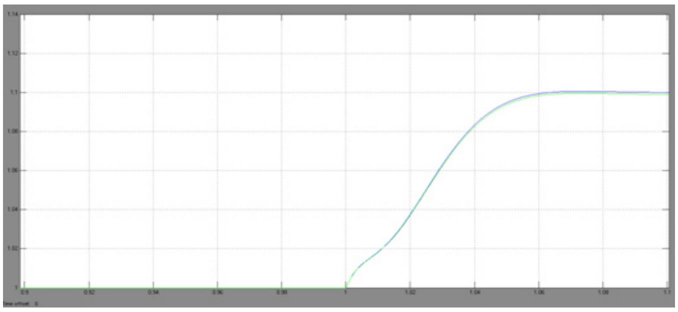

Fig.12.2Vrms pu Signal Performance when Pload=0.8Pinv

B. Case with Same Load Consumption and DG Output:

For this case, the load consumption is set to be the same as the DG output power of 1 pu. The result is shown in Fig.13

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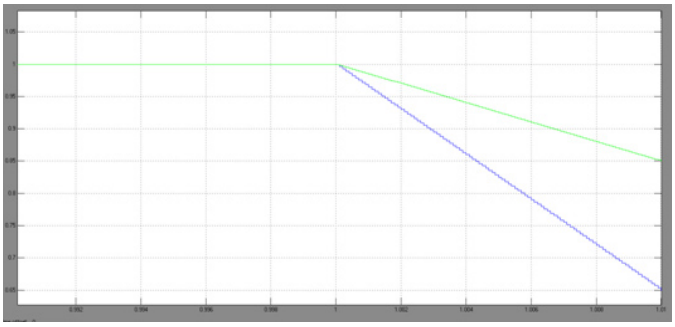

Fig.13.The PVIDMwhen the amount of load consumption and the DG output power are same.

C. Case with Weak Grid:

When the grid is weak, the active IDMs including the PVIDM might cause a stability problem on a power system because they forces intentional changes to system. To test this stability problem in a weak grid, It is shown from the results in Fig.14.

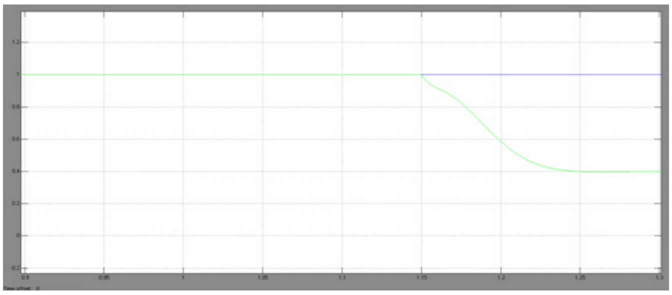

Fig.14.Performances of the conventional and proposed controllers when thegrid impedance is increased.

D. Application of SFIDM to Proposed Controller:

The PVIDM makes the grid to be unstable when the weakness of grid is more serious. Even though this instability can be simply mitigated by decreasing the slope in (2), it might causethe PVIDM to have the NDZ. Therefore, the SFIDM , which can be classified as one of passive IDMs, is applied to remove the NDZ perfectly. When the islanding operation occurs at 1 s, the results are shown in Fig. 15.

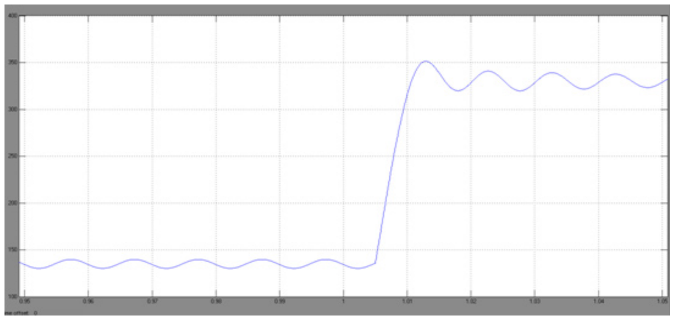

Fig. 15. Comparison of islanding detection performances with the SFIDM.

TABLE I: LOAD SIZES (kW, kVAR):

Load-1		Load-2		Load-3		Load-4	
P	200	P	200	P	3	P	120
Q	20	Q	20	Q	0	Q	12
Load-5		Load-6		Load-7		Load-8	
P	120	P	120	P	120	P	120
Q	12	Q	12	Q	12	Q	12

TABLE II: PARAMETERS FOR CONVENTIONAL CONTROLLER:

PI_1		PI_2		PI_3		PI_4	
K_p	100	K_p	0.1	K_p	100	K_p	0.1
K_I	10	K_I	1	K_I	10	K_I	1
max	100	*max*	100	*max*	100	*max*	100
min	-100	*min*	-100	*min*	-100	*min*	-100

TABLE III: PARAMETERS FOR PHASE-LOCKED LOOP (PLL):

K_p	100	*max*	100
K_I	10	*min*	-100

TABLE IV: PARAMETERS FOR PROPOSED CONTROLLER:

PI for V_{mag}		PI for θ	
K_p	5	K_p	5
K_I	0.005	K_I	0.01
max	100	*max*	100
min	0	*min*	-100

filter impedance, Xs, is 0.1 + j3.7699Ω (i.e, Ls =10 mH, Rs = 0.1Ω).

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VI. CONCLUSION:

The new inverter controller for DG system by using the magnitude and phase of voltage. It improved the system stability by reducing the reactive power oscillations dramatically when the reference real powers were changed. Additionally, it improved the starting dynamic response of inverter with small reactive power variations when compared to the conventional controller. In the viewpoint of protection, the proposed controller provided the better islanding detection performance than the conventional controller by reducing the detection time. It is important to note that the implementation of proposed controller is simpler because it requires only two internal PI controllers. In contrast, the conventional controller normally usesfour PI controllers and a PLL. It would be expected that this study is referred in the design for grid-connected inverter controller of DGs with robust control performance based on renewableenergy resources.

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