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POWER FLOW CONTROL STRATEGY IN DISTRIBUTION NETWORK FOR DC TYPE DISTRIBUTED ENERGY RESOURCE AT LOAD BUS

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This research work presents a feed forward power flow control strategy in the secondary distribution network working in parallel with a DC type distributed energy resource (DER) unit with SPWM-IGBT Voltage Source Converter (VSC). The developed control strategy enables the VSC to be used as power flow controller at the load bus in the presence of utility supply. Due to the investigated control strategy, power flow control from distributed energy resource (DER) to common load bus is such that power flows to the load without facing any power quality problem. The technique has an added advantage of controlling power flow without having a dedicated power flow controller. The SPWM-IGBT VSC is serving the purpose of dc-ac converter as well as power flow controller. Simulations for a test system using proposed power flow control strategy are carried out using SimPower Systems toolbox of MATLAB® and Simulink®. The results show that a reliable, effective and efficient operation of DC type DER unit in coordination with main utility network can be achieved.

Keywords: Distributed Energy Resource (DER), Load bus, MATLAB®/Simulink®, Power flow, SPWM-IGBT Voltage Source Converter (VSC), SimPower Systems toolbox.

1. Introduction

Distributed Energy Resources (DER) are usually installed at the distribution level, close to the load centers, and generate power typically in the range of a few kW to a few MW. DER is capable of injecting different proportions of real and reactive power to the distribution system. It is observed that the peak demand loads are increasing all over the world and the load factor is decreasing year by year. A huge amount of capital investment is required for construction and enhancement of generation and transmission systems. One of the solutions to this problem is installation of distributed energy resources. Electricity generation by distributed energy resources with lower emission technologies contribute, to loss reduction and greenhouse effects through reducing environmental pollution and global warming. Through use of DER, network augmentation and new construction can be deferred, system losses can be reduced and customer's demands may be satisfied instantaneously.

The field of distributed energy resources is a topical area of research in power delivery system. Interest in this field has been rapidly growing among the power planners and researchers. Utilities have recognized the DER as an imperative tool that can partially fulfill the need for new generating stations in order to meet the increasing load demand. The Distributed Generation (DG) option is enjoying a global acceptability to offset the future load growth [1]. Due to the availability of such a flexible option at the distribution voltage level, the distribution network is now being transformed from passive network to an active one.

The demand for flexible power flow control is becoming a technical need that is achieved through the innovative power electronics technologies. These technologies are also being employed due to recent trends in deregulation of electric power industry [2]. The mechanical switched or control equipment simply can not match the fast on-line decision making as required in Energy Management Systems (EMS). Power electronic interfaces are used to connect DC from renewable or distributed energy sources to common AC load bus at 50 or 60 Hz. In this regard the use of power electronics based Voltage Source Converters (VSC) help to control power flow from DC type DERs as per requirement of the load bus. These DC type distributed energy resources may be working in stand alone mode or in parallel with utility supply at the A.C load bus.

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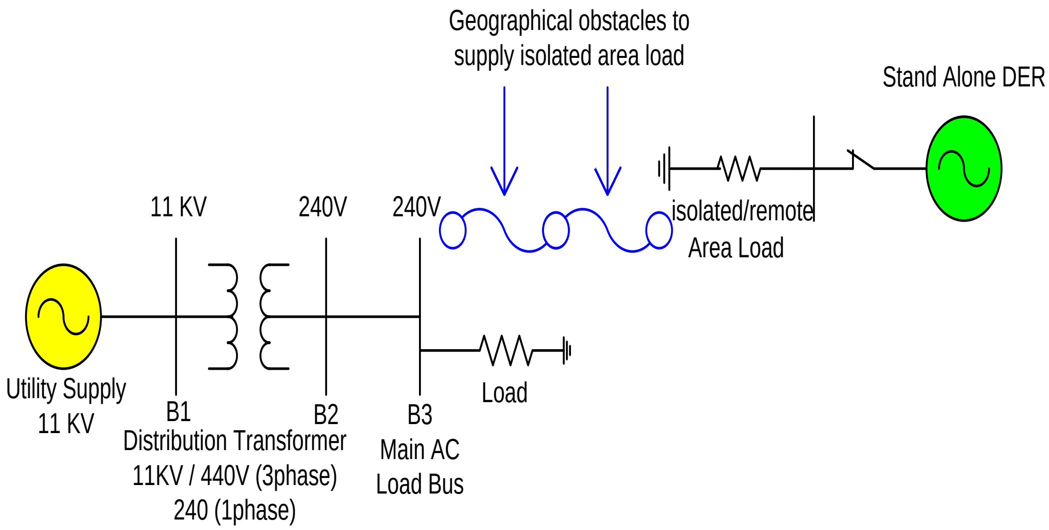

Figure 1. Standby DER supplying isolated or remote area load when utility can't supply isolated area load due to geographical obstacles.

In this research, power flow control with VSC based DC type DER at the load bus is achieved by controlling modulation index, phase angle at the load bus and DC source voltage. We have used sinusoidal pulse width modulated insulated gate bipolar transistor (SPWM-IGBT) VSC with DC type DER on the analogy of the shunt controller of unified power flow controller (UPFC) called static compensator (STATCOM) for power flow control when both DC type DER and utility are working in parallel to serve load bus. In principle, all shunt controllers inject or feed current into the system at the point of common connection (PCC). As long as the injected current is in phase quadrature with the line or bus voltage, the shunt controller only supplies or consumes variable reactive power. Any other phase relationship will involve handling of real power as well [3].

In this paper, first a brief introduction underlining the importance of application of distributed generation and the use of power electronics technology for flexible power flow control is discussed. Existing power flow control strategies at the load bus with utility supply and DER are presented with one line diagrams in section 2. Section 3 of this paper provides brief description of power flow control using DC type DER or static DER with SPWM-IGBT VSC. Section 4 describes proposed power flow control strategy.

Section 5 provides detail about the test system to be used for our analysis alongwith its modeling and simulation. MATLAB® alongwith Simulink® and SimPower Systems tool box [4] is used for modeling and simulation of test system. MATLAB®, Simulink® setup using SimPower Systems tool box is developed for the secondary distribution network working in parallel with a DC type DER. We have used a test system with single phase 240 volt utility supply working in parallel with static DER to analyze power sharing from utility supply and static DER to load. Sinusoidal PWM technique for the IGBT VSC alongwith phase angle adjustment of DC type DER output voltage at the load bus was used to control power flow from DER and voltage at the load bus.

2. Existing Power Flow Control Strategies

There are two existing strategies of sharing DER power in coordination with utility supply at the load bus.

- *Strategy 1:* DER can be used as a stand-alone service to meet customers demand.
- *Strategy 2:* DER can also be used in conjunction with traditional utility service.

Figure 1 shows that in stand-alone applications, DER can serve as remote or isolated area load supply.

In strategy-2, we have further 3 ways of operating DER, connected with utility supply at the load bus to supply load demand.

- Standby switched or rollover mode of operation
- Peak load sharing switched mode of operation
- Parallel operation of DER with utility supply

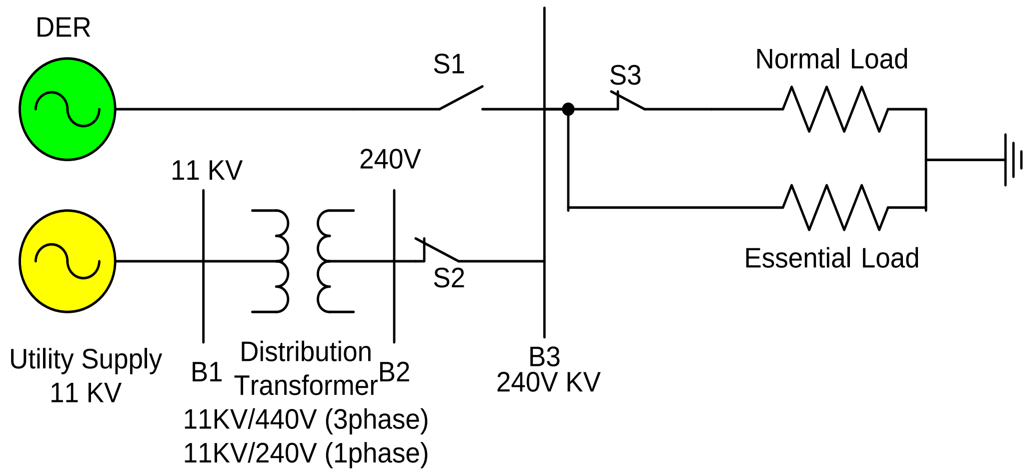

Figure 2. DER standby switched mode operation in conjunction with the utility supply.

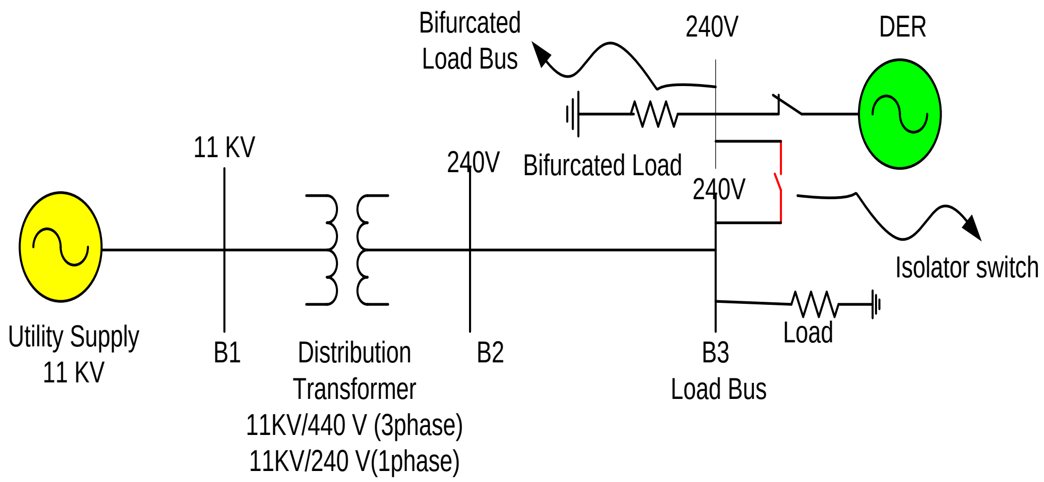

Figure 3. DER supplying load while utility supply is isolated from bifurcated bus.

Figure 2 shows that in standby switched or rollover mode, only one of the two sources that is either utility supply or DER is connected to the load at any one time. Operating like this, if the utility fails while it is supplying the load, then either a manual (slow) or an automatic sensor (fast) operates two switches (S1 and S2). First is to disconnect the utility from the load (S2 opened) and the second is to “roll” the load over to the DER by connecting the load to it (S1 closed). DER will take all loads if its load taking capability is more than the power required by the load, otherwise it will take only essential load. For later case there will be another switch before normal load to isolate it from DER. The opposite switching sequence occurs (S1 opened and S2 with S3 closed) if the utility supply is again connected to the load.

In Peak load sharing switched mode operation of DER in conjunction with the utility supply, load bus is bifurcated into two buses such that additional load during peak hour is shifted to the bifurcated load bus while remaining load is supplied by utility connected with main AC load bus.

The process of shifting additional load during peak hour from main AC load bus to bifurcated load bus is done either manually or automatically through sensor switching. Figure 3 shows this existing load sharing strategy at the main AC load bus in the presence of utility supply as main source and DER is explained.

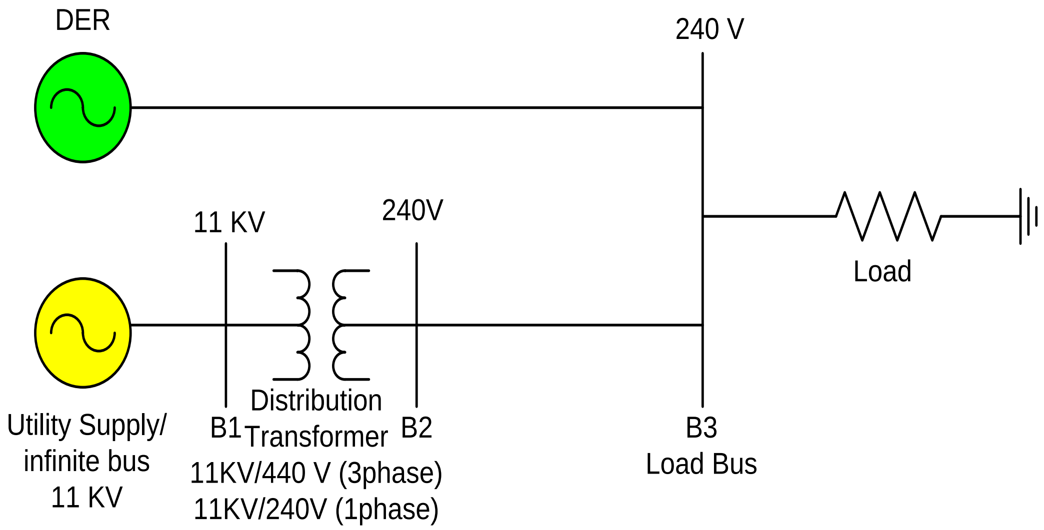

Figure 4. Parallel operation of DER with the utility supply.

Thus, in switched or rollover mode, a brief interruption of service occurs each time the main source fails or peak load demand occurs on the load bus. The time of interruption being whatever is utilized to switch the normal otherwise essential or peak load to the alternate DER source.

Operation of the DER and utility supply connection in rollover mode generally reduces only the duration of time during which the load can be expected to be without power.

Figure 4 shows that in parallel operation, the DER and the utility supply are connected to the load bus. If utility fails, the DER is there to instantaneously take up the essential load, and no complete interruption of power flow to the load occurs because of sudden failure hence frequency of complete interruption is reduced.

In our research work, we are examining static DER or DC type DER working in parallel with utility supply to deliver its all available power to common bus load so that utility is relieved of form serving peak load demand while there is no interruption of supply to critical industrial processes and loads. To achieve this goal DER and utility have a certain arrangement which allows all the static DERs power to flow to load bus.

Conventionally, when a rotary DER unit is made in parallel with utility supply then it will take load only when we increase mechanical power (P_m) delivered by prime mover to DER alongwith its excitation control, whereas, in static DERs this is not the case. The control of power flow from static DER working in parallel with utility supply is discussed in section 3 and 4 of this paper.

There are different advantages and disadvantages of DER-utility supply interconnection but considering pros and cons, when managed properly, two sources of power supply will always provide more reliable power and maintain load voltage profile in an effective manner.

3. Dc Type Der with SPWM-IGBT Voltage Source Converter

A DC type DER system can be designed for a distribution feeder to support the utility by feeding its all available power during peak time of the day or as and when required. As mentioned earlier, DER and utility have a certain arrangement which allows power flow at this particular location. In our work, battery or DC source is representing a constant voltage photovoltaic source and simulated as static distributed energy resource. This DC type DER or static DER can be used to inject energy into the network for power flow control and voltage improvement. Figure 5 shows that connection of DC type DER to the AC load bus is made through a SPWM-IGBT VSC alongwith RLC filter.

SPWM-IGBT VSC connected with DC type DER not only converts DC to AC but also controls power flow from DC type DER by phase angle adjustment of DC type DER output voltage and serves as power flow controller as well. Reverse power flow problem faced by utility is handled by the control logic used to transfer all the available power of DC type DER to load.

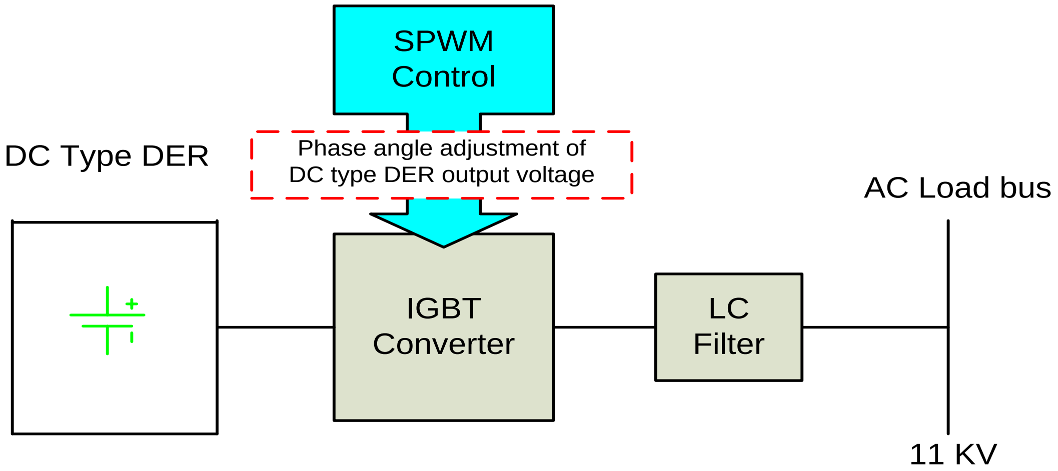

Figure 5. Schematic diagram of DC type DER as DC source (representing constant voltage photovoltaic source) with SPWM-IGBT VSC to serve AC bus load.

The size of the DC type DER depends on the energy injection to achieve a specific voltage for desired power flow for a distribution system, which can be determined from off-line simulation for daily energy requirement from a DER. The VSC system is designed accordingly to regulate voltage of the connection point and hence control power flow from DER.

The VSCs are available commercially in the market. The connection of VSC to the distribution grids has been already developed [5, 6]. Rules for VSC connection have been proposed by standard Australia [7].

The VSC system of the DC type DER has to be synchronized with the utility supply/grid so that it can serve load demand as and when required [8]. As the static DER is synchronized with the utility supply at the load bus, the power injection by DC type DER to load starts by controlling dynamic parameters of SPWM-IGBT VSC. In this way, static DER with phase angle adjustment of DC type DER output voltage at the load bus delivers its available power to load while working in parallel with utility supply.

There are different modulating schemes that can be used to create the variable frequency/variable-voltage configuration in PWM-IGBT VSC [9]. The sinusoidal pulse-width modulation (SPWM) technique is commonly used in industrial applications. In this technique, the width of each pulse in gating or switching signal is varied in proportion to the amplitude of sine wave. The SPWM compares a high frequency triangular carrier with three sinusoidal reference signals, known as the modulating signals, to generate the gating signals for the VSC switches. The frequency of the reference signal (f_r) determines the VSC output frequency and its peak amplitude A_r controls the modulation index 'm' and then in turn the rms output voltage. The ratio of peak amplitude of reference signal A_r to peak amplitude of carrier signal A_c is called modulation index and is written in equation form as

$$m = \frac{A_r}{A_c} \tag{1}$$

Figure 6 shows a PWM signal generator based on SPWM technique. It is used to generate switching signals for the IGBTs in the VSC.

The control system of the SPWM-IGBT VSC will control real power injection from the static DER to the load bus. The power flow from static DER and voltage at the AC load bus is controlled by controlling modulating index 'm' through SPWM control of IGBT VSC and DC source voltage. In case of static DER working in parallel with utility supply, power flow from static DER and voltage at the AC load bus is controlled by controlling the phase angle (δ_1) of DER output voltage alongwith modulation index and DC source voltage through SPWM control of IGBT VSC. DC source voltage is kept constant by assuming that DC type DER is representing constant voltage photovoltaic source. Hence power flow from DC type DER will be controlled by the phase of sinusoidal pulse-width-modulated (SPWM) signal, required to control switching of VSC switches. This phase of sinusoidal pulse-width-modulated (SPWM) signal may be varied to generate DER output voltages with required phase angle to control power flow from DC type DER.

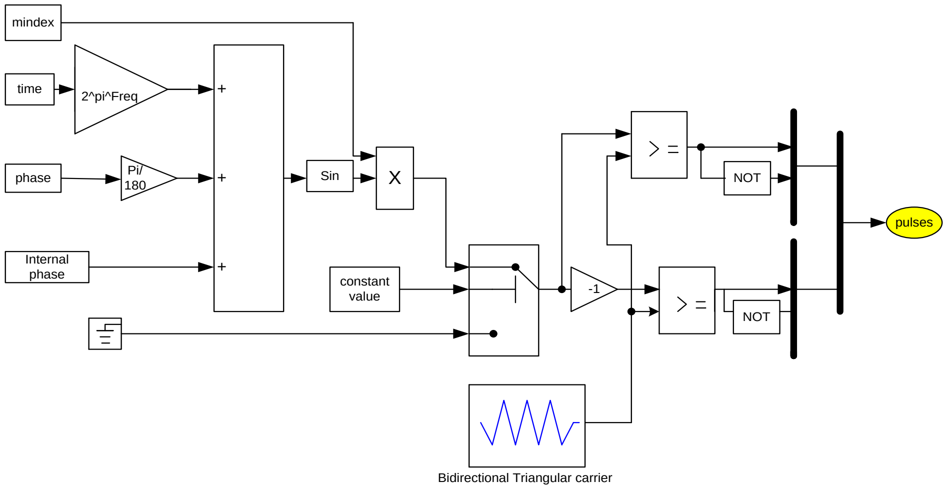

Figure 6. SPWM Generator for the IGBT VSC from MATLAB®, SimPower Systems tool box.

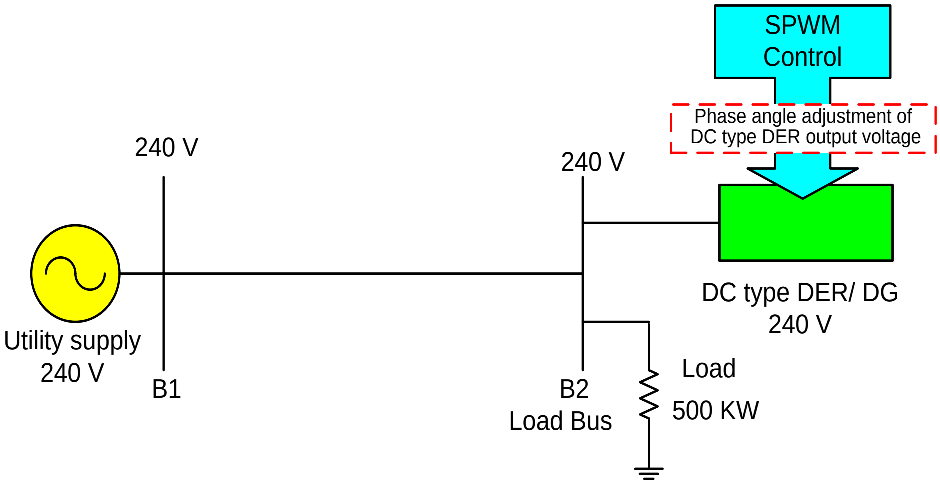

Figure 7. One line diagram of the test system with DC type DER working in parallel with utility supply to serve common bus load.

4. Proposed Strategy for Power Flow Control

In the proposed feed forward control strategy of power flow control for the test system of Figure 7, a bi-directional triangular carrier wave is compared with the sinusoidal reference signal to generate the gating signals for the four IGBTs. These four IGBTs are used in 2-arm SPWM-IGBT VSC with an appropriate switching signal generation topology to produce AC output at 50 Hz. VSC output is further filtered with a series RLC passive filter to reduce harmonics and obtain 50 Hz sinusoidal AC output voltage with rms value of 240V.

To generate gating signals, we used discrete pulse generator block available in SimPower Systems tool box of MATLAB® that generates pulses for SPWM-IGBT VSC. The output pulses are a vector (with values =0 or 1). Depending on the selected mode "Generator Mode", the output vector contains four pulses for 2-arm bridge of Figure 8. Pulses 1and 3 are respectively for upper IGBTs of the first and third arm. Pulses 2 and 4 are for the lower IGBTs. By selecting "internal generation of modulating signals" in the discrete SPWM generator block parameters, we adjusted the modulation index, frequency and phase of the output voltage of SPWM-IGBT VSC. The IGBTs Q1 and Q3 are turned on/off simultaneously using sinusoidal pulse width modulation technique to generate the first half cycle of AC output voltage. The duration of conduction is controlled proportionally to the sine wave magnitude. For the next half cycle, IGBTs Q2 and Q4 are modulated in the same pattern.

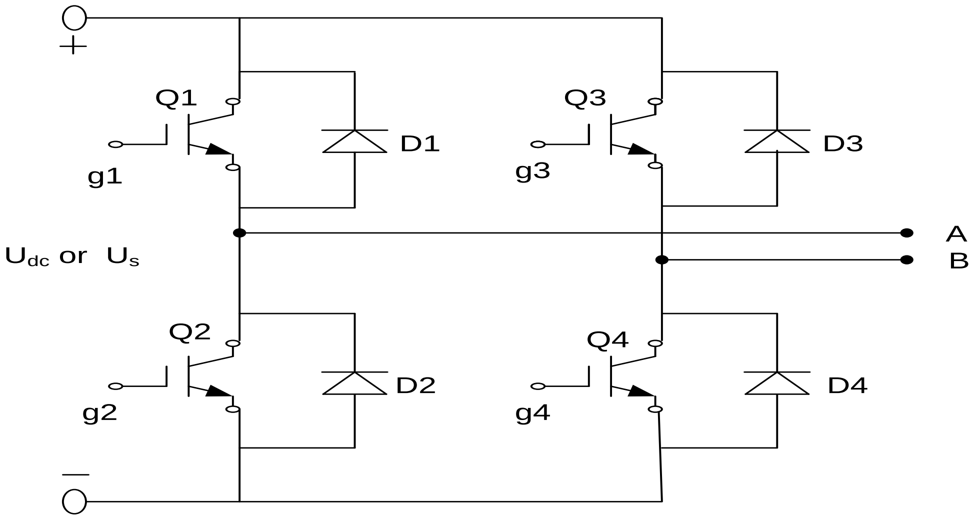

Figure 8. DC-AC single phase IGBT VSC showing location of switches Q1-Q4.

The carrier frequency is set at 1000 Hz and the frequency of output signal is set to required power frequency which is 50 Hz. The modulation index is varied for different injection voltages magnitudes and stays below 1. The phase of output voltage is adjusted according to the requirement of phase angle of the injection voltage.

Mono-polar sinusoidal pulse width modulation relates the magnitude of the fundamental component of the output voltage of VSC bridge to modulation index and input DC voltage as

$$V_{fundamental\ peak} = m_a V_{DC} \quad (2)$$

$$V_{fundamental\ rms} = \frac{m_a V_{DC}}{\sqrt{2}} \quad (3)$$

Where, m_a is modulation index (ratio of amplitude of modulating signal to the amplitude of carrier signal).

The output of the VSC is connected to a series RLC passive filter with output taken across the capacitor with values of R, L & C parameters adjusted such that the damping ratio becomes 0.5. This relates to a quality factor of 1 i.e. at resonant frequency of 50 Hz, the magnitude of fundamental component of voltage at VSC output becomes equal to the magnitude of the fundamental component of output voltage of the filter. However, this will lead to a phase lag of 90° in the filter output. The phase parameter of gate pulse generator is accordingly adjusted to compensate for this lag. Output of the filter unit is then fed to the primary side of a transformer whose secondary is connected in parallel with the utility connection to supply a particular consumer/load.

When static DER is working in parallel with utility supply, the load voltage is made to vary and set at 240V by proper setting of modulation index through SPWM control. By varying modulation index, we can control VSC output voltage and hence load bus voltage alongwith power flow from static DER.

The power flow from utility working in parallel with static DER to serve load is also controlled by regulating the phase difference ($\delta = \delta_1 - \delta_2$) between the DER output voltage, V_{DER} phase angle (δ_1) and Load voltage, V_L phase angle (δ_2) at the load bus. This means that by controlling phase angle ($\delta 1$) of SPWM-IGBT VSC output voltage or DER output voltage alongwith modulation index value, we can also control active power supplied by DER and hence active power supplied by utility to common bus load.

Considering Figure 7 the power flow from static DER to load, given in complex, S_{DER} can be written as

$$S_{DER} = P_{DER} + jQ_{DER} \quad (4)$$

This equation can be rewritten in active power ($P_{utility}$) and reactive power ($Q_{utility}$) as follows;

$$P_{DER} = \frac{V_L V_{DER}}{X} \operatorname{Sin}\delta \quad (5)$$

$$Q_{DER} = \frac{V_{DER}(V_{DER} - V_L \cos\delta)}{X} \quad (6)$$

Where

P_{DER} = Active Power supplied by DER

Q_{DER} = Active Power supplied by DER

V_L = Voltage magnitude at the load bus

V_{DER} = Magnitude of the fundamental component of Filter output

X = reactance of line at power frequency connecting the DER bus to load bus

δ = phase angle difference between the DER bus voltage and load bus voltage

Equations (8) and (9) give the criteria of varying active and reactive power output of the DER. In our current simulation setup, load bus voltage is a constant and hence cannot be changed. DER voltage may also be regarded as constant as static generator voltage variations above a specific limit are also not viable. The reactance of line (X) at power frequency connecting the DER bus to load bus is also known. The angle difference, δ is the only parameter which can be varied to effectively control power flow from a DER. For static generators/DER, the phase of sinusoidal pulse-width-modulated (SPWM) signal required to control switching of VSC switches may be varied to generate DER output voltages with required phase angle.

5. Modeling of Test System and Discussion on Key Simulations Results

Figure 7 shows one line diagram of the test system with utility as main source and DC type DER supplying common bus load for proposed power flow control strategy. Test system consists of the distribution system of 240V. B2 is load bus at 240V, which consumes the active power of 500KW. DC type DER is installed at bus B2 such that its rating is set at 700V so that 240V rms output voltage at load bus is obtained after supplying a load of 500KW. We assume that the DC source or battery (representing constant voltage photovoltaic source), as DC type DER, is a static source with SPWM-IGBT VSC at common load bus.

Four pulse 2 arms SPWM-IGBT VSC is used not only to convert DC type DER output to AC but also it controls to deliver all available power from DC type DER to load. RLC passive filter is used to restrict harmonic currents passed into the network and to obtain sinusoidal AC output [10]. Discrete SPWM generator with its internal control is used to supply switching signals for the four power switches in the 2-arm SPWM-IGBT VSC. Triangular Carrier wave is used and its switching frequency is set at 1000 Hz. This high frequency carrier, to switch IGBTs in the VSC is used to synthesize a sine wave and hence eliminates the low order harmonics. The carrier frequency (f_c) determines the number of pulses per half cycle of reference signal and is found from

$$p = \frac{f_c}{2f_o} = \frac{m_f}{2} \quad (7)$$

Where (f_o) is reference or output signal frequency and $m_f = f_c/f_o$ is defined as the frequency modulation ratio.

The reference signal chosen is sine wave with 50 Hz frequency. This frequency of reference signal determines the fundamental frequency of the VSC output voltage. Modulation index is varied (0<m<1) to control VSC output voltage or DER voltage at the AC load bus.

In our case, DC type DER will be connected in parallel to utility at common load bus when its output is available especially during peak hours of the day to reduce electricity bill. This means that the DC type DER is not always connected to grid.

A MATLAB® / Simulink® based model using Simpower Systems tool box is developed for the test system whose block diagram is shown in Figure 9. This Simulink setup consists of utility supply source working in parallel with DC type DER as DC source. SPWM-IGBT VSC with discrete SPWM generator and passive RLC filter are connected at the output of DC type DER to obtain AC output at 50 Hz to serve load of 500KW at 240V. We have used power electronics library of SimPower Systems to capture non-ideal behavior of power electronics components such as diodes and IGBTs.

Developed model for the proposed control strategy is obtained using components from the SimPower Systems library. For semiconductor devices, a universal bridge is used to allow discretizing of the developed model. The Universal Bridge block in our model implements a power converter that consists of four power switches (IGBTs) connected in a bridge configuration as shown in Figure 8.

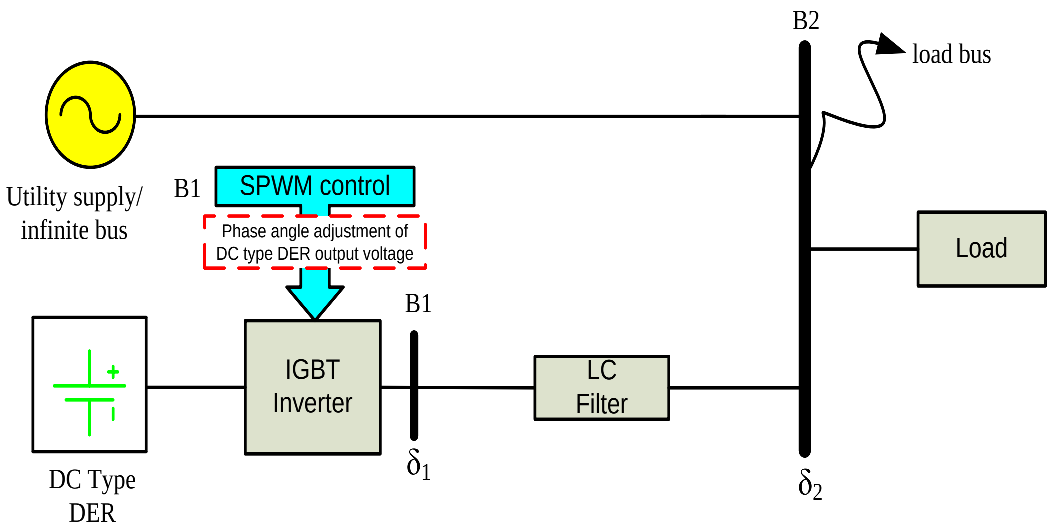

Figure 9. Real time phase angle adjustment for maximum power flow for DC type DER to load.

Ode23tb [stiff/TR-BDF-2] variable step Simulink solver is used to simulate test system circuit model. Ode23tb is an implementation of TR-BDF2, an implicit Runge-Kutta formula with a first stage that is a trapezoidal rule step and a second stage that is a backward differentiation formula of order two. Speed of simulation in the Simulink environment is increased significantly by discritizing the model using the Power GUI tool.

The developed MATLAB® based model is utilized to investigate parallel operation of DER that is interfaced with utility at load bus. Mathematical calculations in Table 1, simulation readings in Table 2 for the proposed system are listed. Various plots relating to Table 2 are shown in Figures 10-13.

In the investigated model based on feed forward control approach phase of the output voltage of SPWM-IGBT voltage source converter of DER is varied to control power flow from DER side. It is evident from Table 1 and Table 2 along with supported simulation results that any increase in phase angle difference between the DER bus and the load bus voltages causes more and more power contribution from DER side.

6. Conclusions

The SPWM-IGBT VSC with battery as DC type DER for power flow control is used on the analogy of the shunt controller of unified power flow controller (UPFC) called static synchronous compensator (STATCOM). The simulation studies with static DER or DC type DER working in parallel with utility supply at the common load bus shows that active power flow to load from static DER with SPWM-IGBT VSC is increased by increasing phase angle (δ_1) at the load bus for the suitable value of modulation index 'm'.

We observed that when power sharing from DER is made to supply some part of common bus load then correspondingly power sharing from utility supply is reduced. This reduction in power sharing by utility helps to reduce utility losses and improve its performance. This also improves load bus voltage and postpones network expansion as load demand is locally met. Reliability of power supply especially during the peak hours of the day is also improved. This shows that the use of DER at common load bus with utility supply saves large investment on constructing new power houses to meet increased peak load demand. Also if load demand is increased and it is to be met by the old power distribution network then either new feeders are to be installed or feeder re-conductoring is to be done.

Implementation cost of the DC type DER as DC source can be justified from postponement of new capacity, reduction in losses and load bus voltage enhancement.

Table 1. Load voltage, DER voltage, utility voltage and active and reactive power contribution by utility and static DER to serve common bus load at various values of "phase angle (δ_1) of DER output voltage" and m = 0.4849. (Calculated results).

No.	Voltage								Current		Powers					
	RMS Magnitude, Volts				Phase, degrees				RMS, Amp	Phase, deg	Active, kilowatts			Reactive, kVARs		
	Utility	DER Voltage & m		Load	Utility	DER		Load			Utility	DER	Load	Utility	DER	Load
							δ_1	δ_2								
1	240	240	0.4849	240	0	0	90	0	2,083	0	500	0	500	0	0	0
2	240	240	0.4849	240	0	15	105	0	2,083	0	371	129	500	-17	17	0
3	240	240	0.4849	240	0	30	120	0	2,083	0	250	250	500	-67	67	0
4	240	240	0.4849	240	0	45	135	0	2,083	0	146	354	500	-146	146	0
5	240	240	0.4849	240	0	60	150	0	2,083	0	67	433	500	-250	250	0
6	240	240	0.4849	240	0	75	165	0	2,083	0	17	483	500	-371	371	0
7	240	240	0.4849	240	0	90	180	0	2,083	0	0	500	500	-500	500	0

Table 2. Load voltage, DER voltage, utility voltage and active and reactive power contribution by utility and static DER to serve common bus load at various values of "phase angle (δ_1) of DER output voltage" and m = 0.4849. (Simulated results)

No.	Voltage						Current		Powers					
	RMS, Volts			Phase, deg			RMS, Amps	Phase, deg	Active, kilowatts			Reactive, kVARs		
	Utility	DER	Load	Utility	DER δ_1	Load δ_2			Utility	DER	Load	Utility	DER	Load
1	240	241	240	0	-0.1	-0.04	2,083	-0.04	498.1	1.9	500	-2.1	2.1	0
2	240	239	240	0	14.9	-0.04	2,083	-0.04	369.3	130.6	500	18.8	15.4	0
3	240	239	240	0	30	-0.04	2,083	-0.04	248.8	251.0	500	68.9	65.6	0
4	240	241	240	0	45	-0.04	2,083	-0.04	143.3	356.4	500	145.3	150.0	0
5	240	239	240	0	59.9	-0.04	2,083	-0.04	67.4	432.2	500	251.2	247.9	0
6	240	239	240	0	75	-0.04	2,083	-0.04	17.9	481.8	500	371.9	368.4	0
7	240	241	240	0	90	-0.04	2,083	-0.04	-2.1	502.5	500	500.3	504.1	0

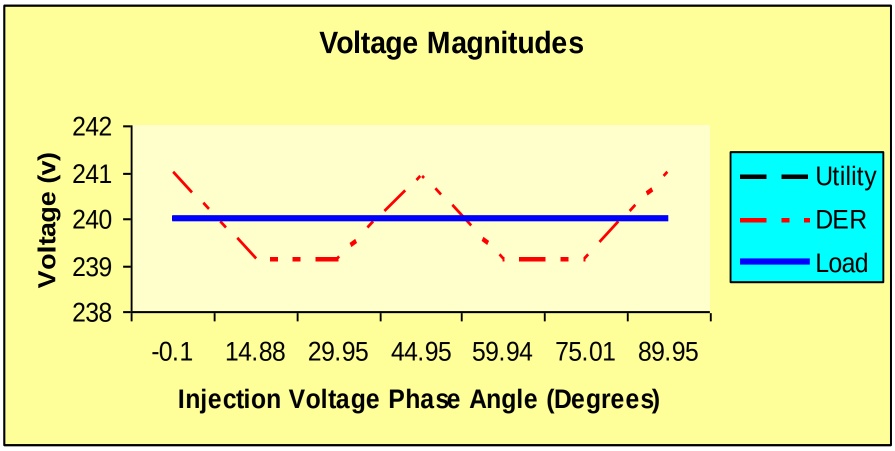

Figure 10. Voltage magnitudes at various values of injection voltage phase angles.

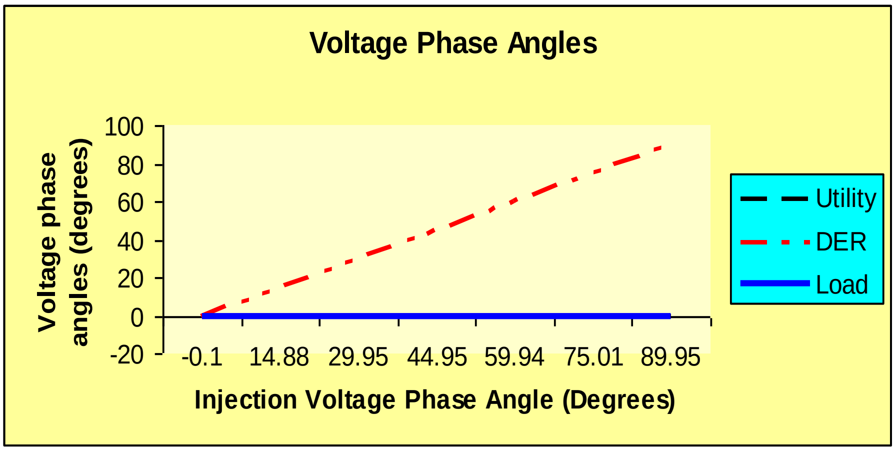

Figure 11. DER, load Voltage phase angles at various values of injection voltage phase angles.

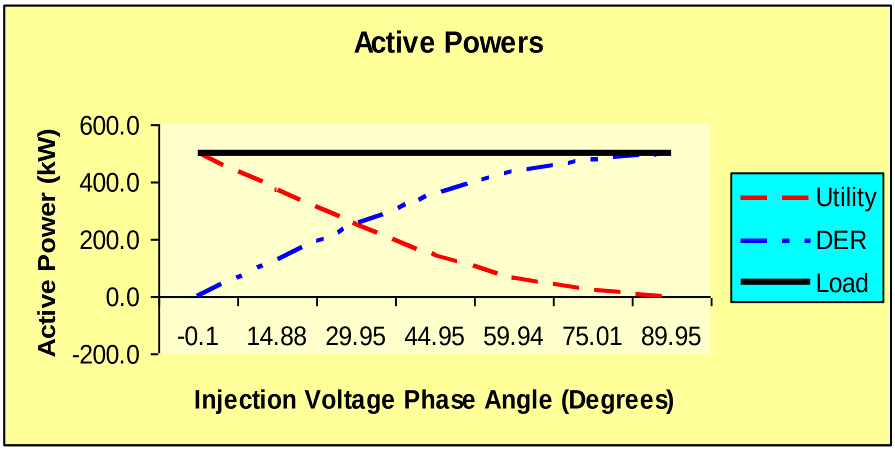

Figure 12. Utility, DER, load Voltage active powers at various values of injection voltage phase angles.

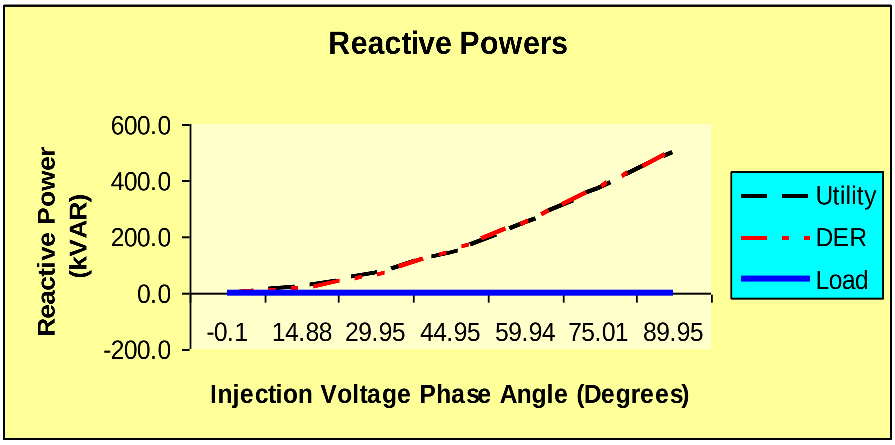

Figure 13. Utility, DER, load Voltage reactive powers at various values of injection voltage phase angles.

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