A SERIES INTERCONNECTION SCHEME FOR DISTRIBUTED GENERATION APPLICATIONS

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ABSTRACT

This paper presents simulation results of an extended voltage control concept of a voltage compensator for distributed generation (DG) grid interconnection applications. The proposed series connection module uses a voltage source converter (VSC) to control the magnitude and phase angle of the series injection/booster transformer output voltages. Because of the series connection, the module's power output varies concurrently with the line loading, therefore, exhibits a load leveling characteristic. During system fault situations, it compensates the missing voltages to effectively deal with voltage sag problems. The concept is suitable for locations where the phase shift in the voltage is not a major concern.

INTRODUCTION

Distributed energy resources (DER) are small, modular power generating and energy storage technologies such as fuel cells, microturbines, reciprocating engines, solar photovoltaics, wind turbines, batteries and other energy storage systems [1]. They are usually designed to inject power into the system by a shunt connected transformer as shown in Figure 1 and the controls of the power outputs are normally set to make it react to changes in demand slowly [2].

DG units planned for individual consumer site installation are small units, located in close proximity to their loads. As such, they see the non-coincident load behavior of the consumer's loads, rather than the coincident load curve shape most typically used in electric system planning [3]. In this case the DG system can play a major role in shaving the peak demand of the feeder if it coincides with the output of the DG [4].

DG provides opportunities for service enhancement, but the potential for DG installations to island and cause safety issue is a major concern of the utilities. Islanding can be defined as a condition in which a portion of an area electric power system (EPS) is energized solely by one or more local EPSs through the associated point of common coupling (PCC) while that portion of the area EPS is electrically separated from the rest of the area EPS [5]. DG providers would incorporate anti-islanding function into their equipment to ensure that the devices can detect electrical island and disconnect from the system properly. Islanding detection techniques can be categorized into passive and active approaches. Details of the islanding detection methods can be found in [6].

For customer site DG installations, issues such as, islanding detection, installation costs and space requirement are important. This paper proposes an extended voltage control concept that addresses some of these issues and augments series voltage compensation's capability to achieve load leveling function.

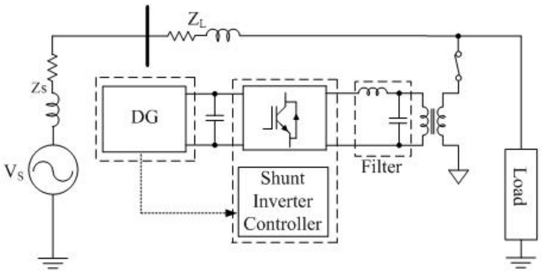


Figure 1 Shunt injection scheme for DG.

SERIES GRID CONNECTION MODULE AND VOLTAGE CONTROL SCHEME

Figure 2 shows the studied grid connection module for DG applications. The structure is similar to that of a dynamic voltage restorer (DVR). Medium voltage switchgears serve to isolate and protect the module in the event of a fault. They also serve as bypass circuit breakers allowing continuous supply during maintenance of the module. The injection/booster transformer connects the module to the distribution feeder. It transforms and couples the injected voltages generated by the VSC to incoming supply voltage. The filter keeps the harmonics generated by the module to a permissible level. Based on the proposed voltage control concept, a voltage controller determines reference voltages and VSC generates the desired series voltages to perform power injection function or to compensate for the voltage sag. The energy storage module obtains power from DG or power system and supplies the necessary energy to the converter via a DC link for the generation of the injection voltages.

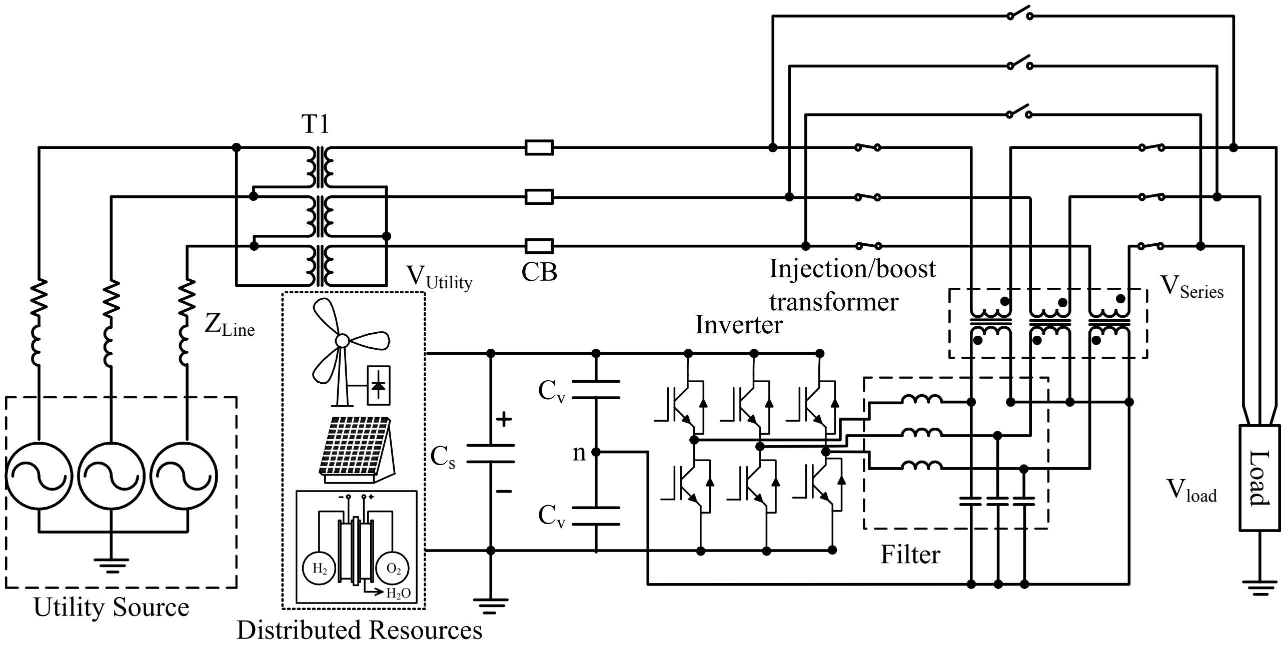


Figure 2 The studied series interconnection concept.

Under normal condition, when the energy level in the energy storage device is proper, the module would inject power to the system. Figure 4 shows the phasor relationships of the mains, load and injected voltages, as well as feeder load current. Assume that after the injection of a series voltage $\vec{V}_{series}$,

$$\vec{V}_{utility} = 1\angle 0 \tag{1}$$

$$\vec{V}_{load} = 1\angle\alpha \tag{2}$$

Note that $|\vec{V}_{series}|$ varies with α and for a feeder load with a power factor angle β,

$$\vec{I}_{load} = |I_{load}|\angle(\alpha-\beta) \tag{3}$$

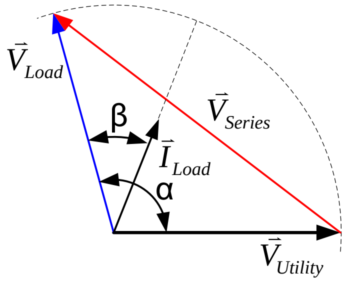


Figure 3 The proposed phase shift control scheme.

$$\begin{aligned} S_{load} &= P_{load} + jQ_{load} \\ &= \vec{V}_{load}\vec{I}^{*}_{load} = 1\angle\alpha \times |I_{load}|\angle(\beta-\alpha) \end{aligned} \tag{4}$$

The powers supplied from the utility and the series injection/booster transformer is

$$\begin{aligned} S_{utility} &= P_{utility} + jQ_{utility} \\ &= \vec{V}_{utility}\vec{I}^{*}_{load} = |I_{load}|\angle(\beta-\alpha) \end{aligned} \tag{5}$$

$$\begin{aligned} S_{series} &= S_{load} - S_{utility} \\ &= 1\angle\alpha \times |I_{load}|\angle(\beta-\alpha) - |I_{load}|\angle(\beta-\alpha) \\ &= (P_{load} + jQ_{load})(1 - 1\angle-\alpha) \end{aligned} \tag{6}$$

Thus,

$$P_{series} = P_{load}(1-\cos\alpha) - Q_{load}\sin\alpha \tag{7}$$

$$Q_{series} = P_{load}\sin\alpha + Q_{load}(1-\cos\alpha) \tag{8}$$

Equations (7) and (8) indicate that the power injection capability of the series module is dependent on the load demand and α. Figure 4 shows the real and reactive power injections under rated loading conditions with different power factors. When the power injection from DG and the energy level of the energy storage unit are high, control vector selector will generate proper reference voltages to control VSC voltage outputs and perform desired power output. DC link supplies the active and reactive power needed with the DG basically charging it during periods of low load. Energy storage unit provides a load leveling or commodity storage capability, so that energy can be dispatched when it is needed.

The concept is suitable for locations where the phase shift in the voltage is not a major concern and its control strategy would depend on the type of load connected. The phase angle jump manifests itself as a shift in zero crossing of the instantaneous voltage. Some loads are sensitive to phase jump, in this case, the load should be protected from them. Some study results have shown that most loads are more tolerant to phase jump and the main task is to maintain the nominal voltage on all three phases.

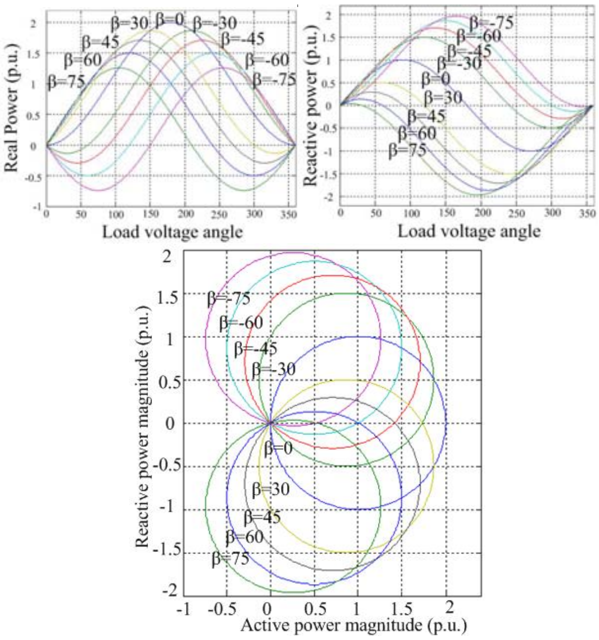


Figure 4 Active and reactive power provided or absorbed by the series interconnection module under different load factor conditions.

SIMULATION RESULTS AND DISCUSSIONS

System parameters used in this study are shown in Table I. Figure 5 shows the voltage and current waveforms in five loading conditions. It is assumed that power factor of the load remains the same in the studied periods. Due to the fact that the outputs of the series module are dependent on the feeder currents and the injected voltages, it is shown in Figure 6 and Table II that the power output of the series module is controllable. The feeder load factor, which is the ratio of average demand to maximum demand (peak load) during a specific period, can be improved by controlling the injected voltage $\vec{V}_{series}$ and consequently, the power output of the series module. In this case, the feeder load factor is improved from 0.407 to 0.585. As shown in Figure 5, instantaneous voltage phase shift waveform distortions will occur when the series module introduces a series voltage. Filters and other measures could be used to relieve the voltage distortion. It is also shown that in conjunction with a real power output, there is a reactive power demand by the series module. To provide local reactive power support, capacitors can be added to the module.

The core of the controller is the phase-locked loop (PLL), the angle used in the synchronous reference frame is used to generate reference vectors that reflect the voltage control modes of desired functions, i.e., power injection or voltage sag mitigation. The difference between the supply and reference voltages produces a voltage vector that can be used to control the inverter output.

Table I Parameters of the test system

Utility Source	Voltage	11.4kV	Linear Load	P=25k W, Q=10k VAR	
	Frequency	60Hz	Filter	L	R_L=1mΩ, L=2mH
Transformer T1	Voltage ratio	11.4kV/480 V		C	3μF
	Capacity	1M VA	Inverter	Switching frequency	10 k Hz
	Connection type	Δ-Y	Energy storage capacitor	19 mF	
Series transformer	Voltage ratio	800/800 V	Fault	Fault types	3Φ
	Capacity	500k VA		Impedance	R=0.02 Ω, X=0.1 Ω

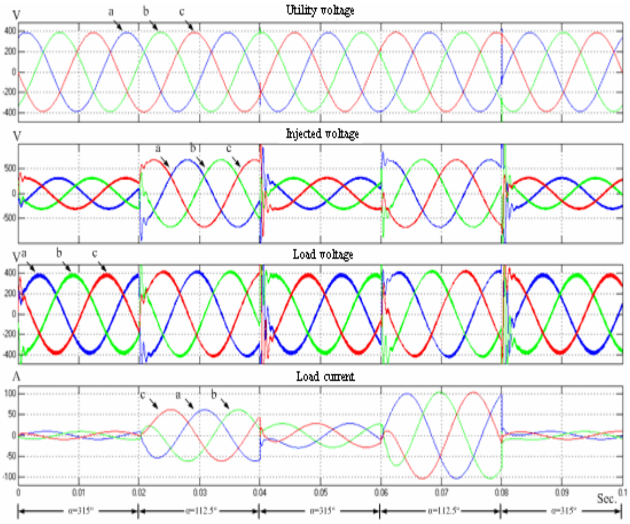


Figure 5 Three phase voltage and current waveforms under different feeder load conditions.

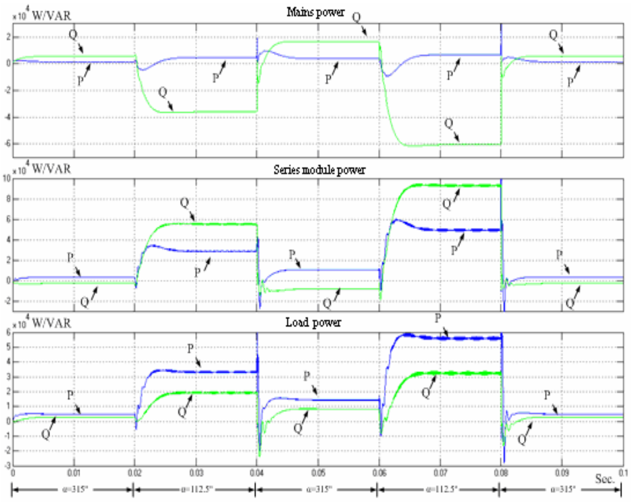


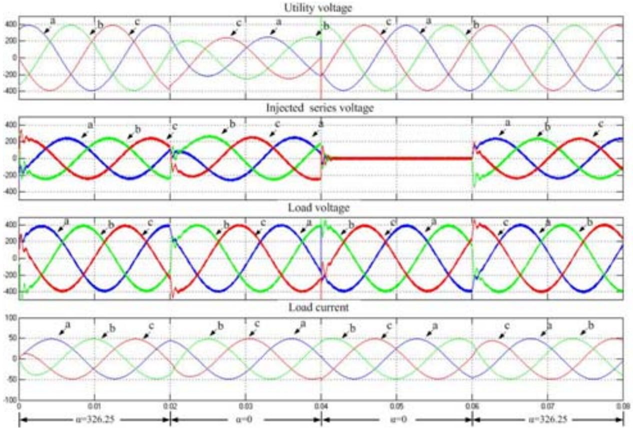
Figure 6 Load demands and power supplied from the mains and the series interconnection module.

There is a possibility that a DG could energize a feeder to which it is connected after the separation of the feeder from system due to feeder faults. This will cause safety and reliability issues. In this situation, if there is no other shunt element between the substation feeder circuit breaker and the series module, the series module will cease power output automatically since there is no current on the feeder. If shunt elements exist in between, test results have shown that the system voltage and frequency are severely distorted with a very small possibility of undetected and several passive islanding detection techniques can be used to avoid islanding operations.

Table II Injected voltages and powers, as well as load factors with different α

Period	α°	Load		Mains		V_{sereis}
		P(kW)	Q(kVAR)	P(kW)	Q(kVAR)	
1	315	4.78	2.76	1.5	5.5	219
2	315	29	16.9	5.25	29	219
3	315	14.35	8.3	4.25	15.6	219
4	315	29	16.9	5.25	29	219
5	315	4.78	2.76	1.5	5.5	219
Load factor		0.565		0.676		
1	315	4.9	2.82	1.31	5.55	219
2	112.5	33.15	19.25	3.6	-36.2	477
3	315	14.7	8.5	3.85	16.65	219
4	112.5	55.7	32.3	5.23	-60.65	477
5	315	4.9	2.82	1.31	5.55	219
Load factor		0.407		0.585		

Four different operation states shown in Figure 7 and 8 are used to exhibit switching operations under different control modes. In the 3rd periods, there is no power output from the series module due to low energy level of the energy storage unit. In period 1, power is injected into the system. It is shown in Figure 7 that after detecting a voltage sag on $\vec{V}_{utility}$ at the beginning of period 2, the voltage controller changes the module function from its power output mode to a voltage sag mitigation mode and performs a pre-sag voltage compensation scheme. After the system voltage return to normal, the module cease voltage output for a period of time. As shown in Figure 8, during voltage sag mitigation period, the power output of VSC could be higher than that in other periods. Figure 8 also shows that VSC can be controlled to reverse power flow to charge the energy storage unit when the load demand is low (period 4).



Figures 7 Voltage and current waveforms during periods with a system fault and low demand.

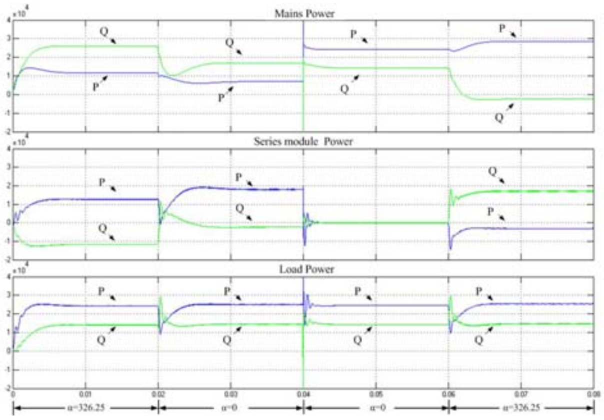


Figure 8 Real and reactive powers during periods with a system fault and low demand.

CONCLUSION

This paper presents a new concept of interconnecting small DG systems to distribution feeders. It is economic for industrial site DER applications since only one converter is used. Simulation results show that the proposed concept has the capability of injecting energy from the storage device to follow the feeder loads and is able to store energy during light load period for peak load use. Compare to a shunt grid interconnection scheme, it should be easier for the proposed series module to prevent islanding operations. The concept is suitable for locations where occasional voltage phase shift is not a major concern.

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