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Harmonic and Reactive Power Control using a Hybrid Active/Passive Power Conditioner based on a Square Wave Source

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Abstract

Control of harmonic and reactive power typically requires high bandwidth, high power converters. As these are conflicting requirements, the cost of such an installation is typically high. In this paper, a hybrid power quality compensator is proposed which consists of a square wave inverter for reactive power compensation combined with a hybrid active/passive filter for harmonic compensation. The filter removes the harmonics produced by the load and the square wave inverter, resulting in a sinusoidal, unity power factor supply current. A suitable control strategy is proposed based on synchronous reference frame transformations and a PI regulator. Control of the reactive current is achieved by varying the bus voltage of the square wave inverter to vary the voltage across the coupling inductor. A simulation model is developed in SIMULINK and used to demonstrate the operation of the compensator.

1. INTRODUCTION

Large industrial loads have a significant capacity to perturb the supply grid in terms of both harmonic power and fundamental reactive power. Typical solutions involve the use of TCR's and TSC's to correct for fundamental reactive power flows and filters to correct for harmonics. The insertion of TCR's and TSC's normally introduces harmonics into the system and requires additional filtering to be present anyway, [1]. Integrated active solutions exist, which can correct for virtually all power quality problems, but these solutions require high bandwidth and high power active elements. These two requirements are in conflict and normally the cost of these installations is relatively high, [2-5].

Much work has been presented in the literature on hybrid active/passive structures for harmonic compensation. These hybrid structures can achieve large harmonic magnitude reductions using an active element with relatively low ratings (typically <5% of the load rating), [4,5].

The rating of the active elements in these structures is reduced by decoupling the active element from the fundamental components of voltage and/or current. Unfortunately this decoupling reduces the ability of the filter to also compensate for fundamental power quality disturbances. Previous work has proposed solutions that incorporate low bandwidth active elements for fundamental compensation, combined with hybrid filter structures to remove load harmonics and harmonics produced by the fundamental compensation, [6,7].

An integrated approach to the design of such systems will enable component sizing and ratings to be optimised for cost in the overall system.

2. PROPOSED COMPENSATOR

A typical compensator for a large industrial load producing power quality disturbances including significant reactive power and harmonic distortion may require a compensator as shown in Figure 1. This compensator requires a TCR and possibly TSC for compensation of reactive power, plus harmonic filters. The TCR and TSC are semi-active components and can vary the reactive impedance of the compensator from an inductive reactance of X_L to a capacitive reactance of X_C.

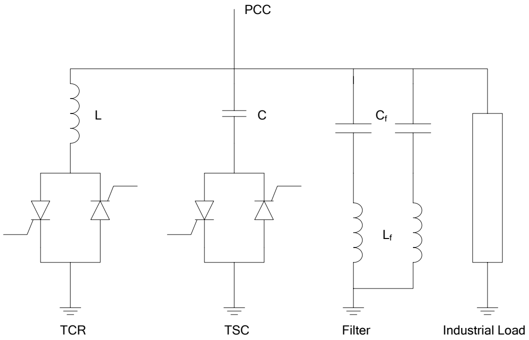


Figure 1. Typical compensator configuration for industrial load.

The inductor and capacitor in this system must be sized to allow the reactive compensator to cover the full range of reactive compensation required for the load. Additionally, the contribution of the filter components must also be considered.

The proposed compensator is shown in Figure 2. This system replaces the TCR and TSC with a single square wave inverter and a coupling inductor. The traditional passive filters are replaced with a hybrid active/passive system, optimised for the particular load. It should be noted that the coupling inductor required for reactive compensation with this system can be much smaller than the inductor required for a TCR in traditional systems.

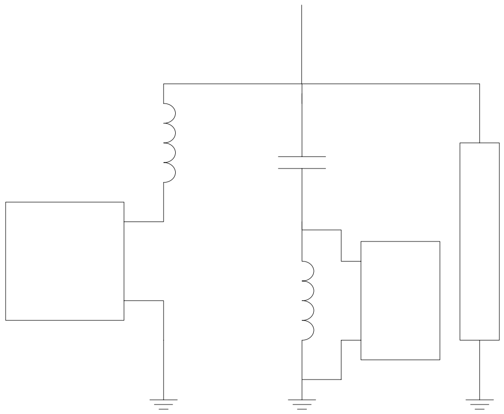


Figure 2. Proposed compensator configuration.

If the phase of V_C is set equal to the phase of V_S, the amount of reactive current injected by the compensator may be controlled by adjusting the magnitude of V_C, which in turn adjusts the magnitude of V_L. To inject leading current, V_C would be greater than V_S (V_L is negative), and to inject lagging current, V_C would be less than V_S (V_L is positive).

Previous work has shown that the size of the coupling inductor affects the range of voltage required in the square wave converter, and the magnitude of the current harmonics produced by the reactive compensator, [6]. Table 1 shows these relationships for a control range of -0.5 to +0.5 pu reactive. The harmonics are calculated with the assumption that the square wave is the only source of harmonic voltage. The maximum value of the harmonic current occurs when the voltage is maximum.

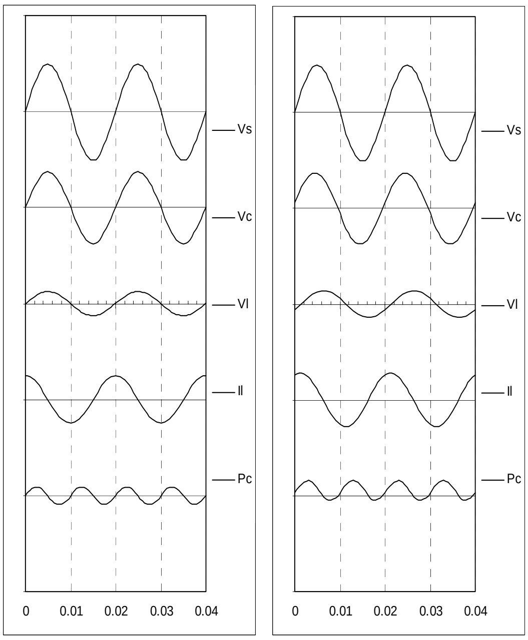
Table 1. Voltage range and harmonics for different values of coupling inductor. (All values in p.u.)

Inductor Impedance	**Voltage Range**	**I_5 (max)**	**I_7 (max)**
1	0.5 – 1.5	0.06	0.03
0.5	0.75 – 1.25	0.1	0.05
0.2	0.9 – 1.1	0.22	0.11

As Table 1 indicates, the harmonics produced by the reactive compensation increase with decreasing inductance. Thus there is a trade-off as this affects the ratings of the filter elements, particularly the active element. This paper only investigates the control mechanisms, but future work will look at the component sizing for optimisation.

3. BUS VOLTAGE REGULATION

A critical element in the control system is the mechanism by which the DC bus of the square wave converter is regulated. Figure 3(a) illustrates the normal operation of the reactive compensator. If V_S and V_C are in phase, then the injected current (I_I) is purely reactive. Under these conditions, the power flows in the square wave converter are purely reactive. If a small phase shift is introduced between V_S and V_C, then a component of the injected current is in phase with V_C, resulting in some real power flow as shown in Figure 3(b).



(a) (b)

Figure 3. Fundamental components of compensator waveforms for different operating conditions.

The DC bus voltage can be raised(lowered) by introducing a small positive(negative) phase shift into the square wave voltage, V_C. Figure 4 shows the relationship between bus charging current and phase shift over a range of output voltages. Although the relationship is not linear, if the phase shift is limited to ±π/4, then this relationship may be approximated as linear.

Using this relationship, a simple linear PI control system is proposed to regulate the DC bus voltage for the reactive power compensator. A block diagram of the bus voltage regulator is shown in Figure 5. A simple model of the square wave inverter and supply was developed to verify this operation. Using the model, it was possible to regulate the DC bus voltage to any desired value.

V_s

PC

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V_L

\-

Low Bandwidth Square Wave Converter

\+

V_c

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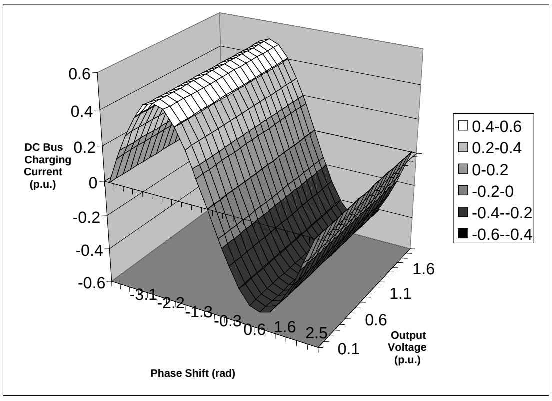


Figure 4. Relationship between bus charging current and phase shift.

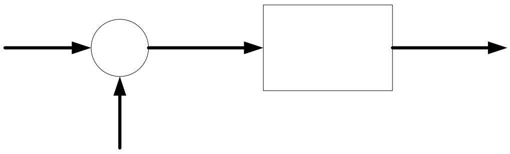


Figure 5. Proposed regulator for DC bus voltage

4. REACTIVE COMPENSATION

Figure 6 shows simulation results for three static cases with reactive compensation. In these simulations the following parameters are used:

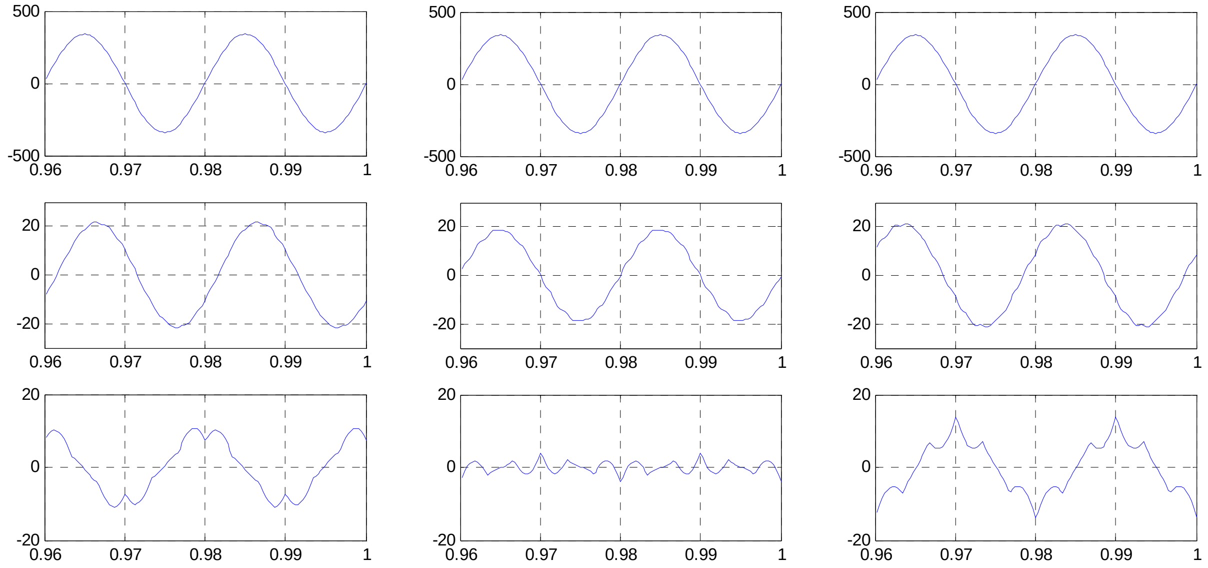
- Supply Voltage = 240V
- Load Current = 15A
- Coupling inductor = 25mH (approximately 0.5pu)

Each graph shows the supply voltage (top graph), the supply current (middle graph) and the compensator current (bottom graph). In Figure 6(a), the compensator voltage is below the supply voltage. The compensator current is lagging and thus the supply current is also lagging. Figure 6(b) shows the case for exact compensation. The supply current is in phase with the supply voltage and the fundamental component of the compensator current is zero. Figure 6(c) illustrates a leading case, where the compensator voltage is greater than the supply voltage.

These static simulations illustrate that reactive compensation is possible and that the additional filter can remove the harmonics generated by the square wave converter.

4.1 Control Algorithm

Figure 6 shows the proposed feedback controller for reactive power. This controller is virtually identical to the bus voltage regulator, however it now regulates reactive power. If a higher(lower) reactive power is required, then the bus voltage must be lowered(raised). To achieve this, a phase shift is applied to the square wave voltage to increase(decrease) the bus voltage.



(a) **(b)** **(c)**

Figure 6. Static simulations with different DC bus voltages

(a) Bus voltage below that required for reactive compensation
(b) Bus voltage equal to that required for reactive compensation
(c) Bus voltage above that required for reactive compensation

DC Voltage

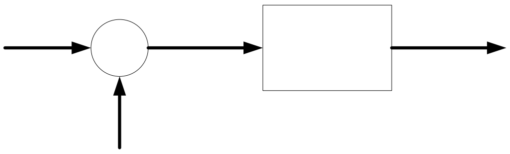


Figure 6. Proposed regulator for Reactive Current.

As the charge rate of the DC bus is limited by the capacitor size, it is required to limit the integral component of the PI regulator, to avoid wind-up. The limit of the integrator is chosen to be just larger than the maximum integral value required for compensation. It should be noted that the integral term is not required in an ideal system as the bus capacitor acts as an integral element, giving this system zero steady state error for a constant input. However, a small integral component is required in practice to achieve compensation for the losses in the square wave inverter.

4.2 Reactive Current Measurement

The amount of reactive current is measured using synchronous reference frame transformations to extract the fundamental reactive component of the supply current. The process (including the controller of Figure 6) is shown in Figure 7.

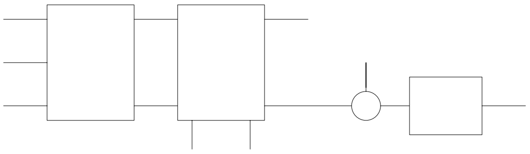


Figure 7. Reactive current control loop.

As shown in Figure 7, the active component of current is not used in the control loop, as it should remain unchanged. The reactive current may be directly used in the synchronous reference frame as input to the regulator.

4.3 Inrush Current Control

During system startup and transient conditions, there will be some low frequency currents flowing in the compensator. This is particularly evident when the system is first energised. The transient during startup can be reduced by using resistors to limit the current. These resistors may be switched out after startup using bypass contactors. During operation however, sudden load changes can cause near DC transient currents in the compensator branch. As the resistance in this branch is low, these currents will take a long time to decay to zero. An additional control loop was added to improve the decay rates of the transient currents in the compensator. This control loop measures the DC component in the supply current and adds a small DC voltage to the square wave output of the compensator, to force the current to zero. The DC voltage is injected by adding a small DC offset to the switch firing controls, so that the switches have a duty cycle slightly above or below 50%.

5. SYSTEM SIMULATION

Figure 8 shows the single line block diagram of the complete system to be simulated. This system consists of a single branch hybrid passive/active filter for harmonic control and a square wave inverter with phase control for the reactive compensation. The supply is modeled as an ideal voltage source with series inductance and resistance. The load is modeled as a sinusoidal current source with a fundamental phase shift. The magnitude and phase shift can be adjusted to yield

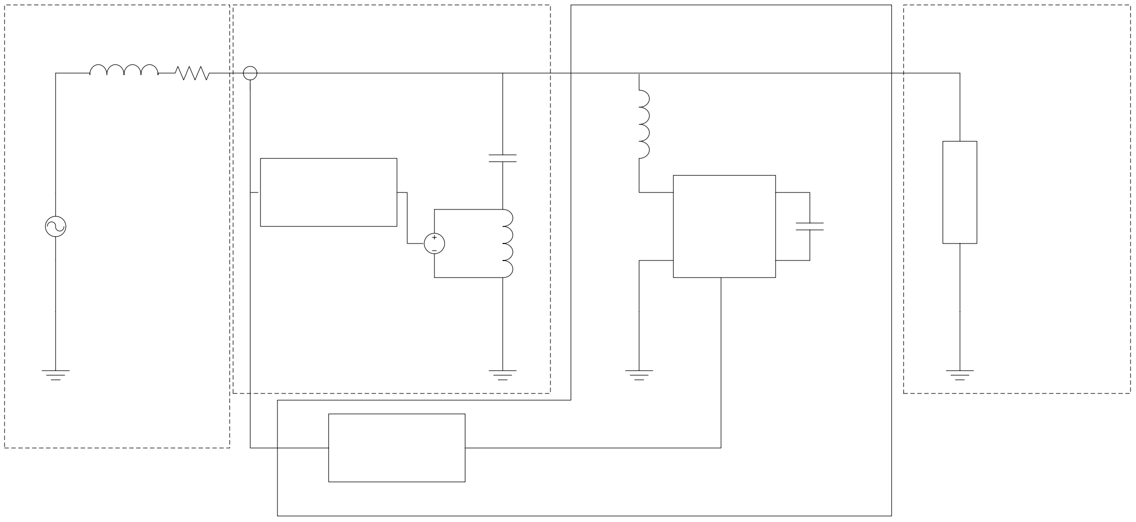


Figure 8. Block diagram of complete system.

any load characteristic. For the simulations presented in this paper, the current magnitude is set to 15A and the supply voltage is 240V.

Figures 9-11 shows typical results for this system for a change in load condition. The simulation began with a purely active load (zero phase shift) and was allowed to settle from startup for this condition. At 0.4 seconds the load was shifted to 30^O of phase shift over 2 cycles. Figure 9 shows the results for supply voltage and current during the transient period. (Note that the voltage in Figure 9 is scaled by 10.)

Figure 9 shows that before and after the load change, the voltage and current are in phase. During the transient, there is some phase shift between voltage and current. Also, the current increases during this period as the DC bus is being charged and some real power is being drawn by the compensator. The supply current magnitude after the load change is lower than before the change. This happens because some of this current required by the load is now reactive and is being supplied by the compensator.

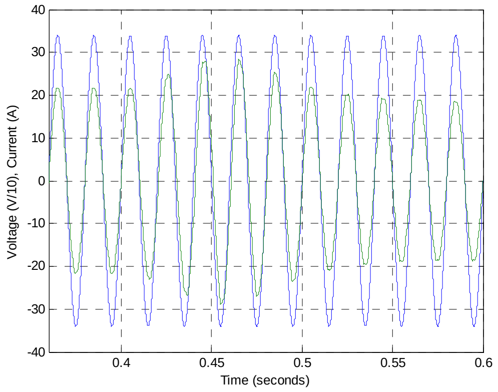


Figure 9. Supply voltage and current during transient load change.

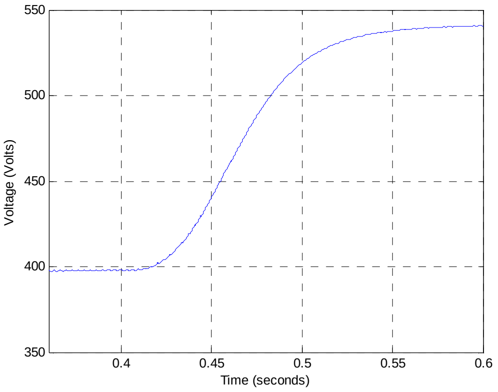


Figure 10. DC bus voltage during transient load change.

Figure 10 shows the DC bus voltage during the transient load change. As expected, during the transient, the bus voltage increases to change the reactive current injected by the compensator.

Figure 11 shows a full set of results for the simulation presented. The waveform for compensator current shows that even with the load set to purely real, there is some reactive current injected by the compensator. This reactive current is required to compensate the reactive component introduced by the hybrid active/passive filter capacitor. After the load change, the capacitor reactive current almost exactly matches the load reactive current and the compensator current reduces to almost zero.

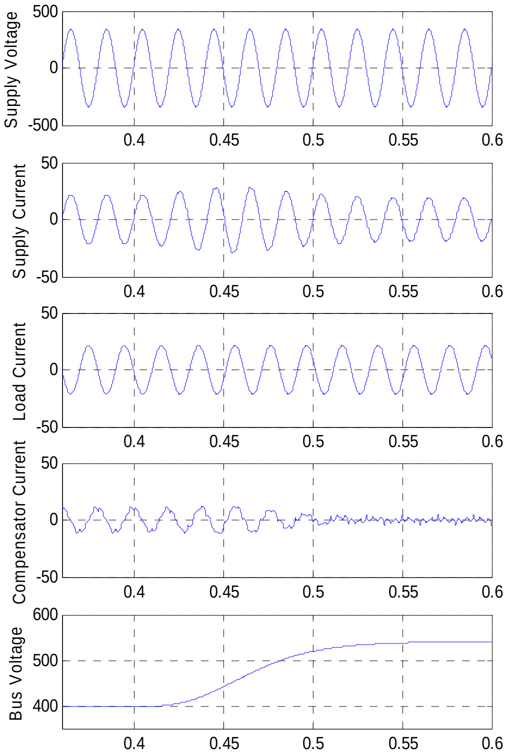


Figure 11. Complete set of results for transient load change.

The duration of the transient is about 10 cycles (200ms). The main factor which influences the duration of the transient is the parameters of the PI regulator. For this simulation, the parameters were chosen experimentally to yield a critically damped response as shown in Figure 10.

6. CONCLUSIONS

This paper has proposed an active compensator for harmonic loads with a significant reactive component. The compensator is based on a square wave inverter, with a coupling inductor. This system could replace semi-active elements such as TCR’s and TSC’s in a power system. The amount of reactive compensation may be varied by varying the DC bus voltage of the square wave inverter (and hence the fundamental component of voltage across the inductor). A simple control strategy is proposed, based on a PI regulator. A model of the proposed system is developed in SIMULINK and used to verify the operation of the compensator for a typical load. Future work is proposed to look at the control structure of the compensator to improve the response, as the response time currently is about 10 cycles.

7. REFERENCES

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