DESIGN OF AN INTELLIGENT CONTROLLER FOR AN ACTIVE FILTER

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Abstract: *A technique of achieving both active current distortion compensation and power factor correction is briefly described. The active filter has been evaluated using a single phase prototype circuit that provides up to 2 kVA of distortion compensation. There is an optimum operating range for the active filter which is determined by the choice of average switching frequency and inverter DC bus voltage. Experimental results, illustrating the filter's ability to reduce the current harmonic distortion components, are presented. On the basis of these experimental results, the design of an intelligent controller, using a Texas Instruments TMS320C30 Digital Signal Processor (DSP), for the active filter is proposed. Such an intelligent controller should be able to determine the most efficient average switching frequency and inverter DC bus voltage to achieve the required current distortion compensation and/or power factor correction.*

Introduction

In the past the devices connected to the power system have drawn sinusoidal currents, even though these may of been drawn with a poor power factor. In recent years there has been a proliferation of power electronic switches that have come onto the market. The main purpose of these switches has been to provide the consumer with the ability to control a wide range of products. In achieving this control the 50 Hz sinusoidal waveform is generally switched and this has the detrimental effect of creating nonsinusoidal supply currents.

Passive filtering has been the traditional method of removing this distortion. However passive filters are non-selective, so they not only filter out the unwanted harmonic components from the supply they are installed on, but they also serve as a "sink" for the distortion components produced by other consumers in the vicinity. They are also generally tuned to remove specific frequency components and are therefore not a completely satisfactory solution when the harmonic composition of the distorted waveform changes. An active filter however is not tuned to remove specific frequency components and can provide varying amounts of harmonic distortion compensation to cater for load changes.

Banks of static power factor correction capacitors provide total correction for only a selection of loads. Active power factor correction techniques, on the other hand, provide total correction for a continuously variable range of loads.

An active filtering system has been developed [1, 2] which can directly cancel the unwanted current distortion and at the same time provide power factor correction. The system is based on current reinjection into the power supply using a high frequency asynchronous controlled current voltage source inverter. The required compensating current, which is produced in real time and is not delayed by any computer processing, is determined using a simple synthetic sinusoid generation technique. Experimental performance and operational characteristics of the active filter are presented. On the basis of the this performance data an intelligent controller which determines the optimum operating point of the active filter is proposed.

The Active Filter System

The active filter monitors the load current I_L, containing the fundamental and distortion components drawn by the non-linear load, and subtracts a synthetically generated sinusoid, which leaves the distortion component of the load current I_C' (Figure 1). The synthetic sinusoid, which is generated in the Signal Processing Unit (SPU), has to be generated in phase with the fundamental component of load current for current distortion compensation (harmonic filtering only) or in phase with

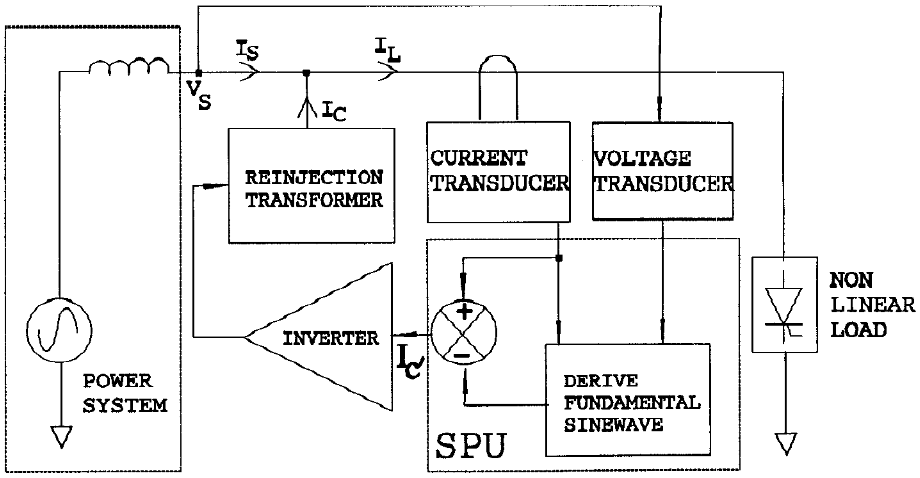


Figure 1: Active Filtering System

the supply voltage V_S to achieve the additional advantage of power factor correction. The distortion components of the load current I_C' are then amplified by the high frequency controlled current voltage source inverter and reinjected back into the power system (I_C) via the reinjection transformer. The current flowing from the supply I_s now becomes nearly sinusoidal.

Previous versions of the active filter have been built using analogue circuitry in the SPU (Figure 2) to determine the phase and magnitude of the load current fundamental component. A bandpass filter (BPF), with minimal phase delay, is used in the phase detection circuit to determine the zero crossings (ZCD) of the load current fundamental. Any shift of the zero crossings alters the frequency of the Phase Locked Loop (PLL), so that it tracks the changes in fundamental frequency. The fundamental component of I_L is synthetically generated by clocking the waveform out of an EPROM and Digital to Analogue Converter (DAC) at a rate determined by the PLL. The magnitude control circuitry determines the amplitude of the synthetic sinusoid produced from the multiplying DAC. The amplitude of the load current's fundamental is obtained by low pass filtering (LPF) and peak detecting the load current waveform. To compensate for the inverter losses the amplitude of the synthetic sinusoid is increased. Real power now flows into the inverter bus capacitor. Any excess power over and above that required to provide compensation for the losses, will increase the inverter DC bus voltage. Thus the inverter DC bus voltage can be controlled by manipulating the amplitude of the synthetic sinusoid.

Experimental Measurements

The active compensation technique has been evaluated using an analogue controlled single phase

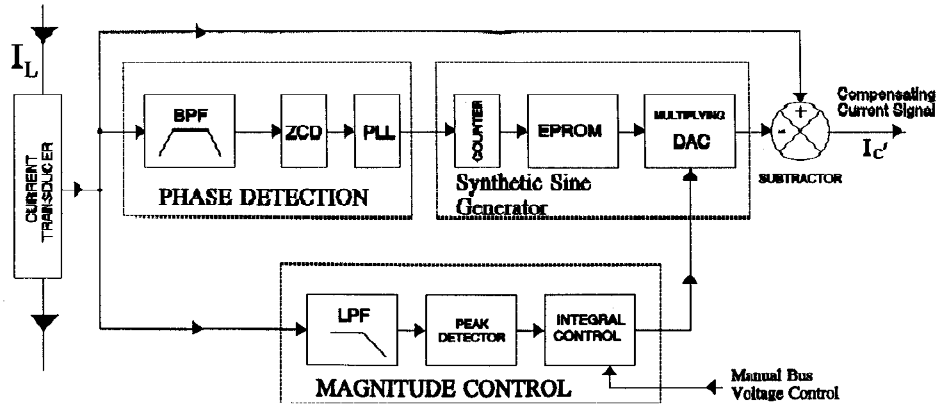


Figure 2: Signal Processing Unit (SPU)

prototype active filter that provides up to 2 kVA of compensation. The high frequency (2 - 40 kHz) asynchronous switching voltage source inverter, which uses IGBTs [3], is interfaced to the power supply via a 2:1 reinjection transformer. The inverter control logic activates either of the two diagonal pairs of transistors of the full bridge inverter, to apply a positive or negative voltage across the transformer connected load. The compensating current I_C then ramps up or down at a rate determined by the time constant of the reinjection transformer and this sets the average switching frequency.

The performance of the active filter can be judged by its ability to reduce the harmonic content of the supply current for a typical non-linear load. The distortion of the load current I_L is evident from Fig. 3(a) and the measured Total Harmonic Distortion (THD), taking into account frequencies up to 1050 Hz, is 42.1%. The variability of the switching frequency is apparent from the compensating current I_C shown in Fig. 3(b). The compensated supply current I_S, shown in Fig. 3(c), is now nearly sinusoidal and the THD has been reduced to 2.6%.

The measured spectra of I_L and I_S respectively are shown in Figs. 3(d) and (e). It can be seen from a comparison of these spectra that the 3rd harmonic has fallen 23 dBV and the compensated supply current 3rd harmonic component is now 35 dBV below the fundamental (1.78% of the fundamental).

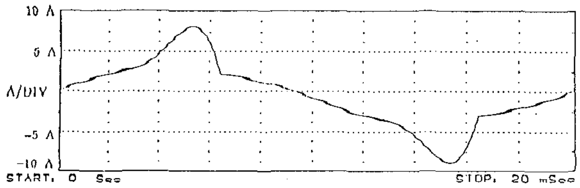
Operating Efficiency:

The operating efficiency of the active filter is based on the real power flow in the system and is determined from the fundamental current that is in phase with the supply voltage. Assuming that the filter is supplied from a strong ac system, the real power flow (P) is the product of the voltage and in phase fundamental current component. The efficiency (ζ) of the compensation system can then be defined by

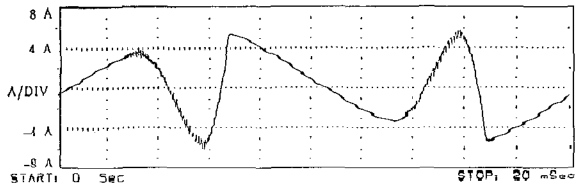
$$\zeta = \frac{P_{\text{load current}}}{P_{\text{supply current with compensation}}}$$

Fig. 4(a) shows the measured efficiency of the active filter for different average switching frequencies and DC bus voltages when providing harmonic compensation for a non-linear load drawing the load current shown in Fig. 3(a). The efficiency improves with low bus voltages because the rate of rise of current has decreased. This decrease in the rate of rise of current effectively lowers the average switching frequency. The switching losses decrease because the inverter is switching at a lower average frequency and a lower bus voltage is applied across the IGBTs. As the bus voltage is increased, for the same average switching frequency, the IGBT switching losses increase and efficiency decreases.

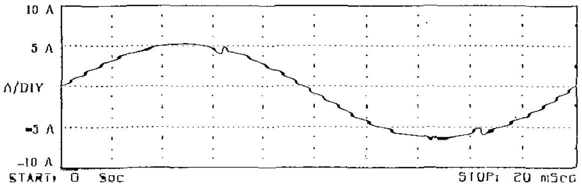
At low switching frequencies the high frequency current excursions around the compensating current signal I_C' increase and the conduction losses of the system



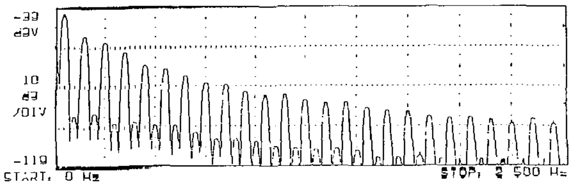
(a) Load current



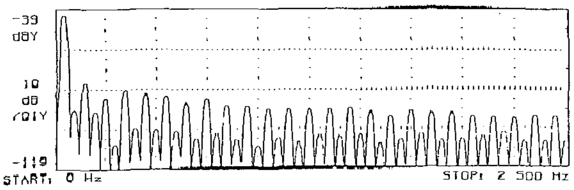
(b) Compensating current



(c) Compensated supply current

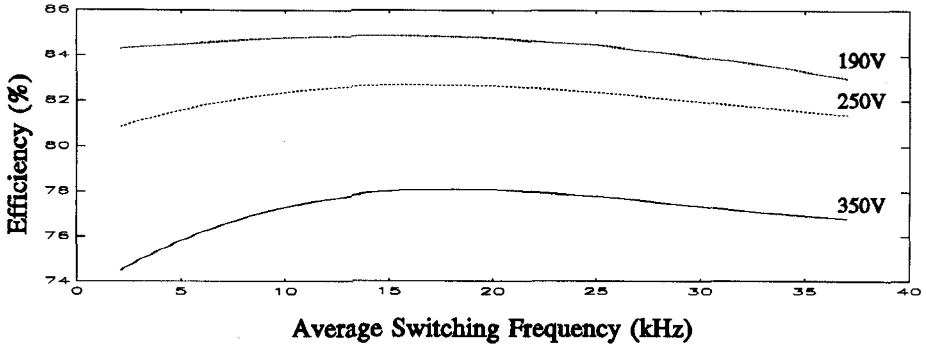


(d) Load current spectrum

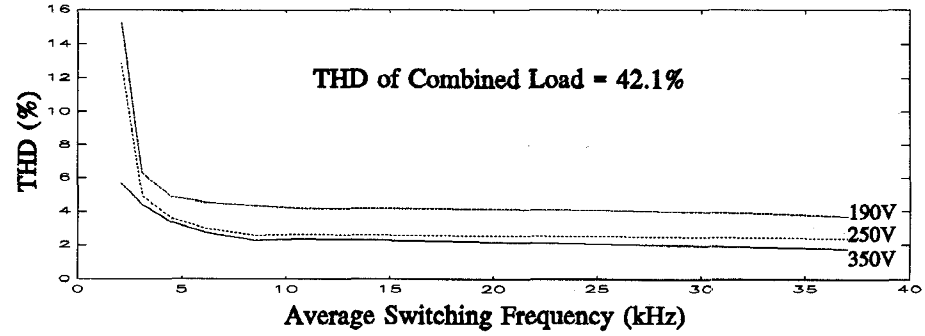


(e) Compensated supply current spectrum

Figure 3: Experimental Steady-State Results



(a) Efficiency of the Active Filter with a Combined Load



(b) Supply THD of the Active Filter with a Combined Load

Figure 4: Measured Performance

are dominant. At high switching frequencies the switching losses of the system become more dominant and thus the efficiency tends to fall. The most efficient average switching frequency for this particular non-linear load is in the range 12 - 20 kHz. To establish an appropriate bus voltage operating level the THD performance of the active filter must also be considered.

The level of supply current THD at various bus voltages and average switching frequencies is shown in Fig. 4(b). At low bus voltages the THD performance is poor because the DC bus has insufficient stored energy to reinject enough compensating current for complete harmonic cancellation. By increasing the bus voltage the active filter can better compensate for the harmonic distortion, however, the incremental increase in THD at higher bus voltages is small. The other factor that can alter the THD performance is the average switching frequency. At low switching frequencies the high frequency current excursions are much larger and thus the harmonic compensation is less than ideal. As the frequency increases, the inverter output current (I_C) can follow the required compensating current signal far more closely and thus the harmonic content can be further reduced.

Clearly then any intelligent controller must be able to quickly determine active filter efficiency and the THD of the compensated supply current. An optimum operating point for the active filter can then be determined by manipulating the inverter DC bus voltage and the average switching frequency.

Intelligent Controller

The system has been designed to be accurate within one degree of the fundamental (50 Hz). The controller therefore has to measure the load current, subtract a sinusoid and send the resulting distortion signal to the inverter within 55μs. This requires a sampling frequency of approximately 25 kHz. A high speed controller is therefore necessary for the basic operation of the active filter and also to perform the task of optimisation, which requires determination of the frequency components of the load and supply currents. To achieve operation in real time, a Texas Instruments TMS320C30 Digital Signal Processor (DSP) has been chosen as the controller. The hardware configuration of the DSP active filter control system is shown in Figure 5.

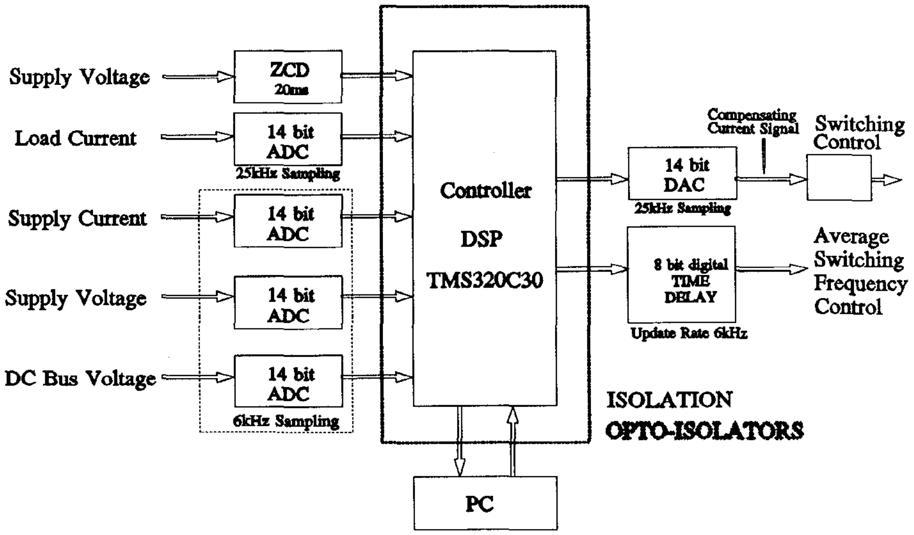


Figure 5: Hardware Organisation of DSP

The load current signal is sampled by a 14 bit Analogue to Digital Converter (ADC) at 25.6 kHz in order to obtain minimal phase delay and a good transient response. The sample rate is variable over a small range (±500 Hz) so that exactly 512 samples occur in each fundamental period. This variation in sample rate is necessary since the fundamental frequency is not constant (variations of ±1% can occur). A variable sample rate is an added advantage when performing Fast Fourier Transforms on the input data. The use of exact sampling does not require windowing of the input data to reduce effects such as spectral leakage. The fundamental frequency voltage zero crossing (ZCD) is used to synchronise the sampling frequency and the generation of the reference sinusoid. The supply voltage, supply current and DC bus voltage ADC's sample at a lower rate of 6.4 kHz as the required bandwidth of this information is 2.5 kHz. This sampling frequency is achieved by dividing the load current sampling frequency by four (to 128 samples) to enable synchronisation of the ADC's data. Isolation is provided between the ADC's, DAC's and DSP by optocouplers. This is necessary because the various measurement and control functions are carried out with respect to different reference potentials.

The load current sample is sent to the DSP, where the instantaneous sinusoid value is subtracted, leaving the distortion signal. This distortion signal is analogous to the analogue signal I_C' shown in Fig. 1. The reference sinusoid, which is stored in a 512 point lookup table in order to provide the DSP with the greatest amount of processing time for the intelligent control, corresponds in the analogue control case to where it was stored in an EPROM (Fig. 1).

The magnitude of the reference sinusoid is controlled by the voltage level on the inverter DC bus capacitors and the magnitude of the fundamental of the load current in a similar way to that depicted in Fig. 2. The DSP controller will be used to maintain the required DC bus level while retaining a good transient response to changes in load current magnitude.

The resulting distortion signal, corresponding to I_C' in Fig. 1, is fed via a 14 bit 25 kHz DAC to the inverter switching controller. Switching frequency is altered by an 8 bit digitally controlled time delay. This allows the average switching frequency to be adjusted over the range two to forty kilohertz.

The DSP will also act as a fault monitoring system and provide the standard protection controls necessary for a power electronic inverter. Performance information and system status will be calculated by the DSP and transferred to the personal computer (PC) for graphical display. In addition to harmonic compensation the DSP controlled active filter will be able to provide a range (0 - 100%) of power factor correction.

Determination of Optimum Operating Point

The optimum operating point of the DSP controlled active filter to achieve a given supply current THD at maximum efficiency is load dependent.

Therefore this optimum operating position must be determined on-line during operation of the active filter. The DSP controller can alter the active filter's performance by adjusting the inverter DC bus voltage set point and average switching frequency. Via the PC, the operator is able to specify the required supply current THD and/or the required minimum efficiency.

To determine the operating point under steady state conditions, it is possible to scan all the combinations of average switching frequencies and DC bus voltages. The intelligent controller then could make a decision based on measured efficiencies and supply current THDs, taking into account operator requirements. However in the real world, the load is continually changing and the approach of scanning every possible operating point is not feasible.

An on-line algorithm must therefore be used to find an optimum operating point which takes into consideration the operator requested targets. Therefore a search based approach is proposed to find this operating point. Initially the system will start at a low average switching frequency since the active filter always has a lower efficiency under this operating condition. The system will then alter the switching frequency, via the 8 bit time delay, and search along the operating line of constant bus voltage (Fig. 4(a)) until maximum efficiency is determined. The DSP controller will then maintain a constant average switching frequency while altering the operating DC bus voltage until the THD of the supply current is minimised or below that specified by the operator. Using this new value of DC bus voltage a second search along the operating line of constant bus voltage is carried out to find the new maximum efficiency and required new switching frequency. Maintaining this new switching frequency the DC bus voltage is again altered until the THD of the supply current is minimised or below that specified. When such a control loop is implemented in the DSP controller the system will constantly try to improve operating efficiency and supply current THD.

Conclusion

A technique for achieving supply current distortion compensation and power factor correction has been briefly outlined and experimental results presented. On the basis of these, and other, experimental results and measurements a high speed intelligent controller has been proposed for an active filter. The controller uses a TMS320C30 DSP and the operator interface is provided by a PC. A hardware description of the DSP controller and a comparison with an analogue active filter is given. By using intelligent control the operation of the active filter can be optimised to ensure that the consumer is achieving the required level of compensation at the most efficient operating point.

References

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