THE ADOPTION OF NEW CONCEPTS IN AC TRACTION INTERFERENCE CONTROL

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Introduction

Brush Traction has a long history in the development of ac drives including the World's first locomotive using inverter fed induction motors. With the introduction of 3-phase drives into the U.K. came a new interest in signalling compatibility. This led to major development programmes in which the system design for signalling compatibility became a dominant factor. After the introduction of ac drives onto the U.K. dc railway, attention turned to the ac railway and the compatibility of pulse converters.

Cecube teamed up with Brush Traction to develop an advanced modulation system for pulse converters, to offer significant advantages over existing forms of control system. This paper describes some of the background to this and presents the new modulation system for the first time.

1. HOW THE INTERFERENCE PROBLEM AROSE

The approach to signalling compatibility was fairly relaxed until the introduction of chopper drives. Prior to this camshafts were not seen to cause interference on dc supplies and on ac supplies only harmonics of the supply frequency were expected to be generated and thus would not coincide with track circuit frequencies. With the introduction of chopper drives, the harmonics produced directly by switching of the power circuit needed to be controlled. A standard solution is to fix the chopper frequency (and hence the harmonic structure of the return currents) and use a frequency monitor to check that the switching frequency was correct. This has been applied to several systems without the stringent levels of safety analysis to which we are now growing accustomed.

When three phase drives were introduced in the 1970's it was recognised that the variable frequency of the inverter could be a new source of problems. The variable output frequency and switching regimes would naturally produce a source of harmonics over a wide range of frequencies. What was not recognised at the time was the magnitude of interference currents caused by existing rolling stock and substation systems. These effects are not negligible and may be caused by transient operating conditions, unbalances in the many sub-systems or the power collection system and its tolerances.

The work leading to the introduction of three-phase drives marked the beginning of a major investigation into the generation of harmonics from drive systems **(1)**. This has led to the design of new control systems and a deeper understanding through this work that included sophisticated computer modelling. In parallel with this has been the goal of increasing safety on the railways and the developing process within Railtrack for obtaining safety cases. The result of this has been a better understanding of drive systems and new methods of harmonic control **(2)**, together with an improving understanding about the behaviour of signalling systems.

2. THE SIGNALLING INTERFERENCE RISK

Signalling systems that use the track as an electrical circuit for train detection may be sensitive to currents of as little as 100 milliamps, possibly less. The same track is used for the traction return currents that may approach levels of 7000 Amps. The root of all the problems experienced in signalling compatibility is the low dynamic range between the sensitivity of track circuits and the magnitude of components of the traction return current which could interfere with the signalling.

Clearly the signal to noise ratio is not very good. Traditionally the interference thresholds have been defined as simple amplitudes/durations at specific frequencies. This is the basis of Railtrack's GS/ES 1914 standard. For some signalling systems the mechanisms that define the response to interference currents are more complicated and some are less well understood. A new approach is needed to take this into consideration.

Managing a traction system design to meet a signalling interference specification requires consideration of: -

Detailed understanding of the system design
Normal steady state operating conditions
Transient operating conditions
System tolerances
External effects

With dc supplied inverter systems the main element for controlling harmonics has been the pulse width modulation (PWM) system linked to the switching speed of the power devices. Brush Traction have employed a sophisticated PWM system which, in association with a total system approach to signalling compatibility has ensured correct operation in service. Making the drive produce the low levels of harmonics required by signalling systems is, in itself, a major achievement. Demonstrating it can meet the ever more demanding safety targets is yet another.

3. TOTAL SYSTEM PROOF OF SAFETY

The initial approach was to apportion to the traction system a proportion of the overall system safety target. The same apportionment was applied irrespective of the type of signalling system and it's relative susceptibility levels or interference mechanisms. This placed a burden of "proof" on the manufacturers to meet quantified levels of mean time between wrong side failures. This has been problematical for a number of reasons but in particular there was minimal understanding about the behaviour of signalling systems to signals that they were not specifically designed to receive.

The solution adopted on the ac drives first introduced onto the 750V dc railway was to transfer the problem to a separate Interference Current Monitor Unit (ICMU). This was designed to the appropriate safety standards and would trip the unit out if the safety levels were exceeded. This has been criticised by some, but the reality to date is that all manufacturers have had to use some form of ICMU to deal with simple track circuits such as 50Hz vane relays. For dc supplied inverter drives there are some failure mechanisms for which detection is impracticable without directly monitoring the interference current. If an external monitor is used it can protect the vehicle and railway system to a quantifiable extent. This has the added benefit that changes made to the propulsion equipment, for reasons of performance upgrade for example, will not affect the safety case for monitored signalling frequencies.

Initially, confidence was gained from having a device that renders the vehicle safe, no matter what fails either on the train or within the power supply system or on vehicles on the same network. This was a crucial factor in gaining acceptance for the operation of three phase drives in the UK. The main reasons to criticise the use of a monitor are reduced reliability and susceptibility to external effects such as supply interruptions. These reduce the operational reliability of the vehicle while improving the safety of the railway system as a whole.

The crucial lesson from all of this work, for the purpose of this paper, is that for some of the simple track circuits, some form of monitoring of the return current is necessary in order to detect failures in hardware or software that may not be self-revealing. Considerable effort was applied to devising systems that would be able to reach the required safety levels without compromise, but without the use of an external monitor. The method described in section 4 for ac systems is a direct descendent of work carried out to solve these problems on dc fed inverters.

With ac supplied drives the situation is exactly the same for simple signalling systems such as dc track circuits. These track circuits do not utilise the natural characteristics of the ac system in the way in which their designers were expecting. In practice, the asymmetries in systems create low frequency components in the return current which the track circuits interpret as dc. These track circuits and other simple ones such as reeds require some form of monitoring in order to be able to demonstrate acceptable safety. With ac in general, however, there is an added complexity caused by the inter-modulation effects between inverter and converter systems. This makes theoretical analysis more complex.

Safety cases need in depth knowledge derived from process of designing the whole drive system for signalling compatibility. The policy employed by Brush Traction has been to develop such an understanding of the drive system, and to create software simulations that make the process manageable. The safety management process is becoming better defined and a flexible approach that can deal with changing situations is a major asset.

Assuming that the traction harmonics can be adequately reduced in normal operation the main problem areas are associated with fault conditions and transient behaviour. Therefore one of the major design goals for pulse converter systems on ac supplies was to devise a system which was fault tolerant.

4. THE FAULT TOLERANT APPROACH

To achieve the aim of high operational reliability the system design must ensure that total shutdown is less frequent than for methods described previously. So, why might fault tolerance be a desirable way forward?

a. It is the only approach that can satisfy desired levels of safety and operational reliability simultaneously.

b. It is not essential to have considered every failure mode before it happens because there are only two consequences: either no discernible change to the risk area, or total system shutdown.

Fault tolerance is a concept frequently applied to software where “n version” defensive programming, formal methods and development tools can be used to manage risk. However, long-term reliability issues in traction applications are normally dominated by hardware rather than software considerations. These include small errors or biases in drive electronics, degradation in power electronic devices, partial failure of passive power components and malfunctioning of system sensors. A fault tolerant system needs to address all of these hardware factors to be successful.

To appreciate how this is possible it is necessary to consider a lesson from classical feedback theory in the form of **figure 1**.

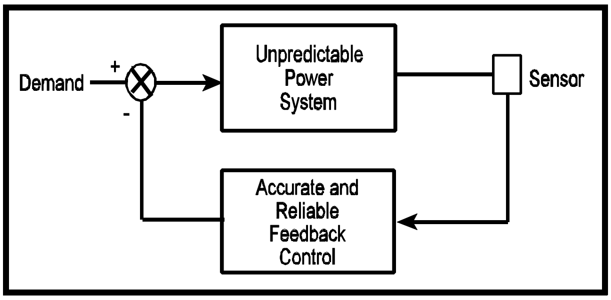

Fig. 1 Elementary feedback applied to correct an unpredictable power system

The feedback concept is not new to traction, as almost all modern drives contain some form of current control loop that takes this form. This smooths out non-linearities and irregularities of the traction system, typically in bandwidths of 10Hz, 25Hz or perhaps even 100Hz. Unfortunately these bandwidths do not encompass most signalling frequencies. What is required in this instance is not a 100Hz but rather a 10kHz bandwidth. How can this be done? A pulse width modulation feedback control system termed Entropy PWM offers the answer.

4.1 Characteristics of asynchronous and synchronous PWM

Entropy measures the degree of disorder of a system. The precise statement of this idea is known as the second law of thermodynamics. It states that the entropy of an isolated system always increases, and when two systems combine the entropy of the combined system is greater than the sum of the individual entropies. That is to say the system is more chaotic than before. A central paradigm of chaos theory states that minute initial condition differences evolve into quite different paths or strategies **(3)**. Pursuing this analogy one can visualise the switching harmonic energy to be entirely chaotic, while the underlying fundamental voltage is the fractal component, visible on the output, and resulting from the chaotic activity. This type of operation moves us away from conventional synchronous PWM where the ratio of carrier cycles per mains cycle is a fixed integer multiple, to one of naturally occurring asynchronous strategies where the ratio is non-integer and possibly varying with time.

The simplicity of comparing a demanded sine wave reference with a triangular waveform, means that natural sampling can be operated either asynchronously or synchronously. The latter produces (by Fourier series) a well-known spectrum (see **figure 2**), which can be interlaced

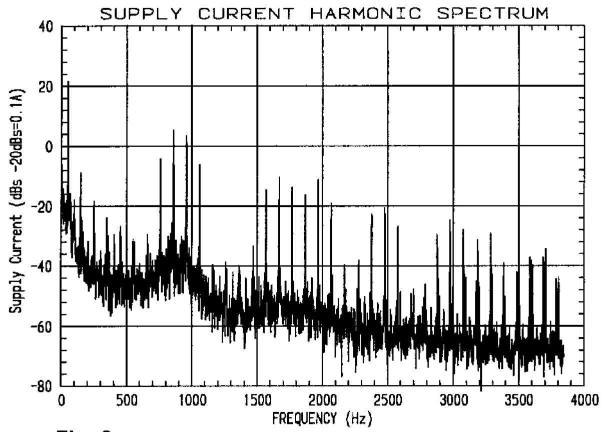

Fig. 2 25kV AC CONVERTER USING SYNCHRONOUS NATURAL PWM

with multiple pulse converters, operating other carrier phase shifted versions, to remove bands of harmonics at multiples of the converter switching frequency. This cancellation only appears on the primary supply side so does not help the transformer secondary losses. For traction converter applications any PWM system must avoid low frequency harmonics as these generate higher loss currents in the transformer. Unfortunately vehicle operational reliability normally dictates that signalling compatibility and voltage distortion requirements have to be satisfied under conditions of converter malfunction. Hence, the probability of converter outage allows interlacing benefits be used as a factor in a harmonic probability sum, but total reliance on interlacing for signalling compatibility is rarely possible.

The main disadvantage of asynchronous PWM operation is the possible generation of subharmonics. In general terms the subharmonic and partial harmonic frequencies will be found at f_{sub}, where $\mathbf{f_{sub} = m.f_{carrier} \pm n.f_{supply}}$

and $f_{carrier}$ is the modulating carrier frequency
f_{supply} is the mains supply frequency
m is any positive integer
n is a configuration dependent positive integer

In practice, on the converter ac side, it is only necessary to consider low order values of m, and odd integers for n if it is a single phase converter system (n would take non-triplen integer values for a 3 phase system). The amplitude of each component is complex to compute and this is dealt with later, but in general terms, larger values of n become increasingly insignificant on an inversely proportional to n basis. Taking a simple example, if f_{supply} = 50Hz and $f_{carrier}$ = 220Hz, then major subharmonics could be expected at 170Hz, and 270Hz, 70Hz and 370Hz, -30Hz and 470Hz, etc. These partial harmonics are in addition to the normal harmonics of the supply frequency which may also be present. An example of the extra components is shown in **figure 3** where the

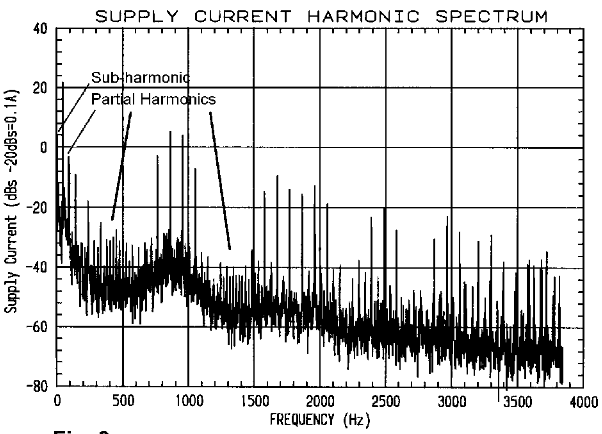

Fig. 3 25kV AC CONVERTER USING ASYNCHRONOUS NATURAL PWM

synchronous sampling process of figure 2 is allowed to run asynchronous. Production of these subharmonics has, until recently, always persuaded traction engineers to employ synchronous strategies for both converters and inverters.

Entropy PWM (EPWM) operates using asynchronous natural sampling in its normal mode, with an instantaneously variable carrier frequency. The interlacing concepts of multiple converters may still be applied, however, the high frequency spectrum is highly modified. There is no evidence of individual carrier frequency multiples present. Equally importantly the lower frequency spectrum is distributed (spread) with many of the characteristic switching frequency harmonics disappearing into the noise floor. The spectrum is superior to the synchronous form of natural sampling when analysed over a narrow bandwidth (resolution). As the bandwidth is widened, towards that of the mains supply frequency, the spectrum starts to appear similar to the synchronous form. Evidently the spread spectrum benefits of EPWM are maximised for narrow band track circuit signalling systems.

The EPWM spectrum can be considered as a series of harmonics added to a base noise level which results from the use of asynchronous switching and instantaneous voltage feedback. The precise characteristic of the spectrum depends on the type of modulator implemented within the EPWM system. The use of feedback is important in achieving exactly the voltage required despite the continuing change in the PWM structure. This makes EPWM equally (or more) acceptable to the converter control system than a conventional PWM by virtue of the accuracy to which the fundamental is guaranteed. As a result the system does not generate unwanted low frequency subharmonics, as would an open loop asynchronous PWM, which otherwise deteriorate control system performance. Instead the harmonic energy is redistributed to higher frequency parts of the spectrum. In this respect there is an analogy with off line harmonic elimination optimised PWM which moves energy from the eliminated harmonic(s) to increased component levels above the switching frequency.

It is possible to separate the PWM modulator from the surrounding EPWM control system, and the type of spectrum which results has a character governed by the modulator. Any type of modulator that is of an instantaneous form will work, and two have been considered. These are natural sampling PWM and the sigma delta modulator **(4)**. Regular sampling, although it gives spectral results very similar to natural sampling, cannot usefully be applied to EPWM because it restricts instantaneous control. On their own both natural sampling and delta modulation would give results composed of predictable fixed frequency harmonics well above the base noise level when incorporated into EPWM. The switching frequency control then redistributes the harmonic energy. However, the EPWM base noise level will generally not be as low as the noise floor for a deterministic, symmetric, PWM system. Thus, a rise in the noise floor has in effect been exchanged for the capability of modifying each pulse at any point in its carrier cycle. This capability can be optimised to produce control and spectral benefits.

The randomised harmonics are decomposed with a 3dB bandwidth and amplitude determined by Boys **(5)**. However, not only do supply harmonics decompose (or spread), but so to do inter-modulation components from the link. This means that a much smaller link capacitor can produce acceptable results. This can be visualised by thinking of the EPWM converter system as instantaneously changing it's strategy as the link voltage moves away from the desired value, in a manner that restores the desired value, thus imitating the effect of capacitance by feedback. Conceptually at least, given an appropriate form of converter and load control, it is possible to eliminate the capacitor bank.

4.2 EPWM structure for robustness

The objective is to integrate self-monitoring (or checking) into the EPWM package, such that non-compliant operation elsewhere in the converter system is proven to be reflected in the behaviour of the PWM. The capability of making relatively simple self-monitoring checks is based upon the exceptional robustness of the system. To appreciate how this can be achieved the feedback structures of EPWM, as shown in **figure 4**, should be understood.

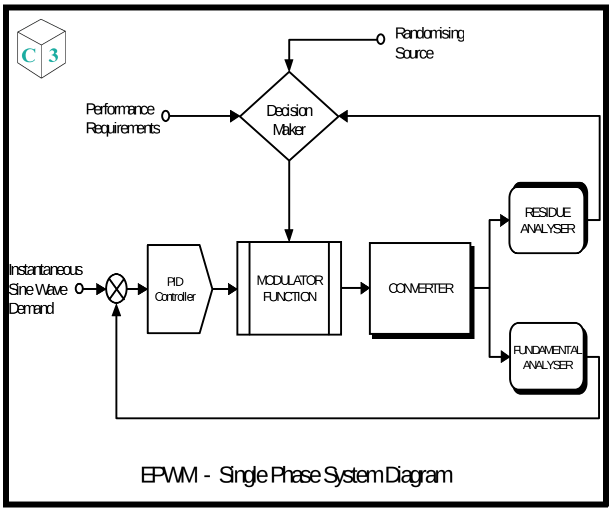

Fig. 4 High Level EPWM Block Diagram

The PWM system is in turn a subsystem of a converter control regulator, which will generate a PWM demand (frequency and modulation depth) required to meet the wider objectives of link voltage regulation and power factor control. This control system does not need to be particularly high performance to benefit from the inclusion of EPWM. In practice, the robustness of EPWM has been found to improve the outer loop control. This robustness comes from the ability of the feedback system to very accurately estimate the instantaneous fundamental voltage. Having determined the fundamental, the remainder of the measured ac voltage are harmonics, from which the dc (or below supply frequency) terms are extracted. These two feedback quantities govern the EPWM i/o transfer function. All that remains is to put a suitable modulator in the forward path to complete the loop. The ac converter input voltage is the required measurement input, or alternatively the link voltage and converter input current may be used instead. As the latter two signals are normally available for other purposes, this becomes the preferable choice of measurements. EPWM will successfully eliminate dc from the ac supply, for any link ripple not synchronised to the supply frequency. Synchronous components could also be eliminated if ac side measurement is made instead, but the extra transducer could be in conflict with reliability requirements.

The advantages of EPWM are:-

a. No fixed frequency harmonics

- Better spread of harmonic energy across the spectrum
- No continuous tones - less likely to pick and hold a track circuit
- Less likely to cause resonance on overhead line
- Audible noise from electrical equipment diminished

b. Robustness

EPWM is:-

- Tolerant to converter volt drop asymmetries
- Tolerant to firing pulse delay variations
- Tolerant to link filter ageing and partial failure

c. Reliability

- **Potential for self monitoring - checks for malfunction both in hardware and software**
- Peak clipping mode allowing operation at overcurrent limit
- Not solely dependent on correct interlacing for multi-converter compliance
- On line switching frequency variation to suit temperature conditions

d. Harmonic levels

- Small dc component in primary under all converter operating conditions
- Immune to variation with load shedding
- Not degraded by inter-modulation from load harmonics
- Takes advantage of track circuit response times and follower delays

4.3 Comparison of EPWM and regular sampling harmonics

To examine a cycle of EPWM waveform does not suggest anything harmonically spectacular, but the cumulative cycle by cycle effect is to

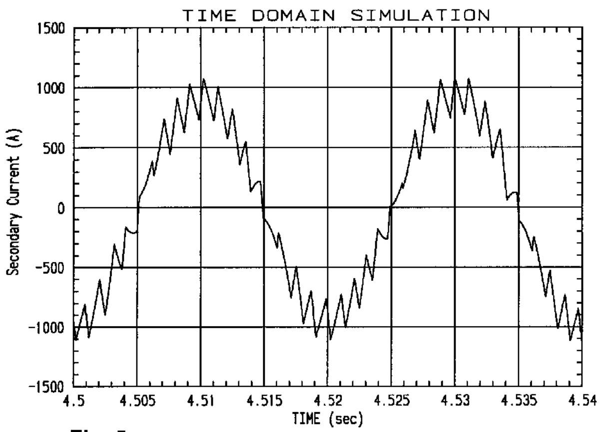

Fig. 5 25kV AC CONVERTER EPWM WAVEFORM AT 0.5MW

distribute the energy across the spectrum by a randomising of the carrier frequency (see **figures 5 and 6** comparing EPWM and regular sampling (RSPWM) time waveforms). To achieve this

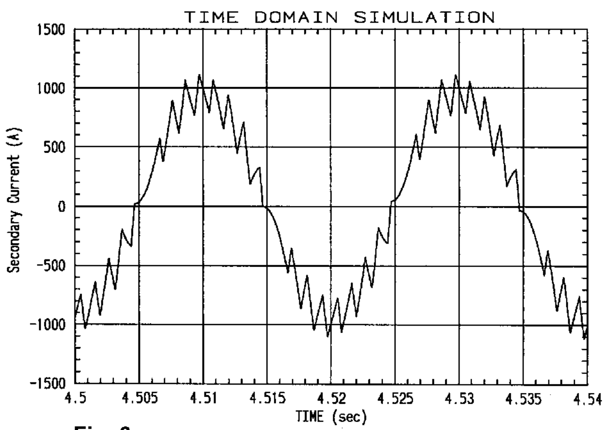

Fig. 6 25kV AC CONVERTER RSPWM WAVEFORM AT 0.5MW

requires two distinct criteria to be fulfilled; first the PWM is accurately following the demanded voltage, and secondly, that the instantaneous carrier frequency is totally unrelated to the supply frequency. In the case of natural sampling EPWM this is achieved by choosing the carrier frequency according to a deviation from the nominal carrier frequency defined by a pseudo random binary number (PRBN). Clearly, the faster the update of the waveform generation, the better the accuracy of the waveform. In the prototype a 30ms time step was used. With a normal PWM system this would be quite inadequate in terms of placement accuracy of the PWM edge, but on EPWM any fundamental voltage error is compensated for in the successive pulses. This is why **the EPWM system is so tolerant to the effects of hardware timing errors and tolerances described in section 4.2**. The error residue just serves to add to the entropy of the process, enhancing the random appearance of the spectrum.

From the above discussion it is possible to generate a random waveform which accurately reflects the required fundamental voltage, but without evidence of distinct harmonic components. In the EPWM spectrum all frequencies are equally weighted, whereas in conventional synchronous systems only the harmonic frequencies are significant, leaving the non-harmonic components to normally have zero contribution. This results in EPWM offering true spread spectrum harmonic structure, where each harmonic has its energy equally distributed around its centre frequency, and where no preference for the harmonic frequency is

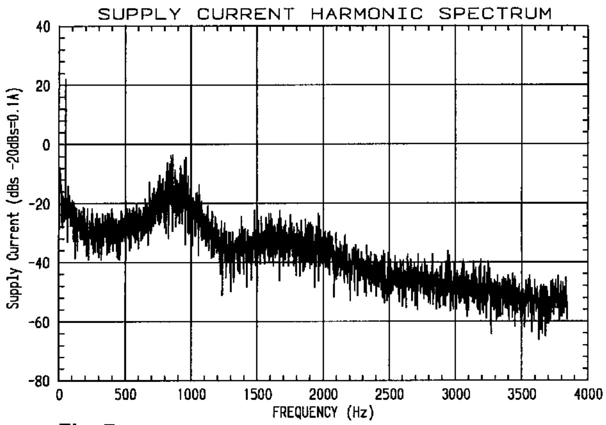

Fig. 7 25kV AC CONVERTER SPREAD SPECTRUM EPWM

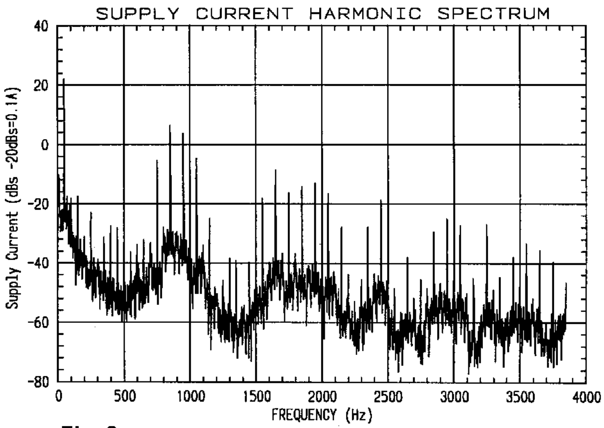

Fig. 8 25kV AC CONVERTER USING RSPWM

exhibited. Compare the normal spectrum of RSPWM and EPWM in **figures 7 and 8**, noting the reduction in the peak harmonic levels.

The understanding of the processes involved in EPWM generation leads the observer to appreciate that harmonic energy is being distributed around the spectrum at each change in PWM strategy. The consequence is that harmonic levels at a particular frequency can only be sustained for a very short period of time. By this means the response time dependence of track circuit signalling systems can be introduced into the compatibility argument. This is achieved by the unifying of steady state and transient operations into a characteristic spectrum which is similar for both conditions. To demonstrate this point, consider the equivalent EPWM and

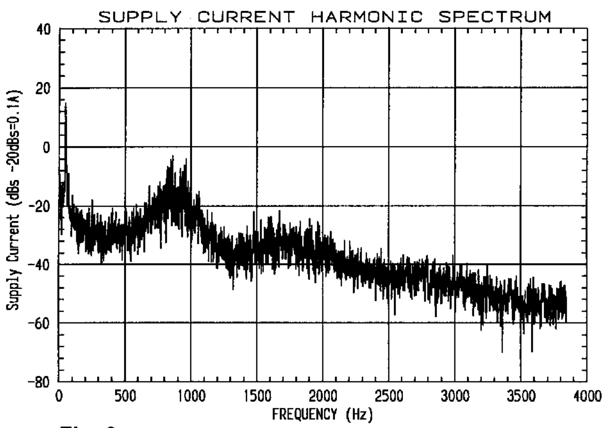

Fig. 9 25kV AC CONVERTER USING EPWM - Load Shedding

RSPWM converter spectra depicted in **figures 9**

and 10, operating under the same supply conditions when transient load shedding.

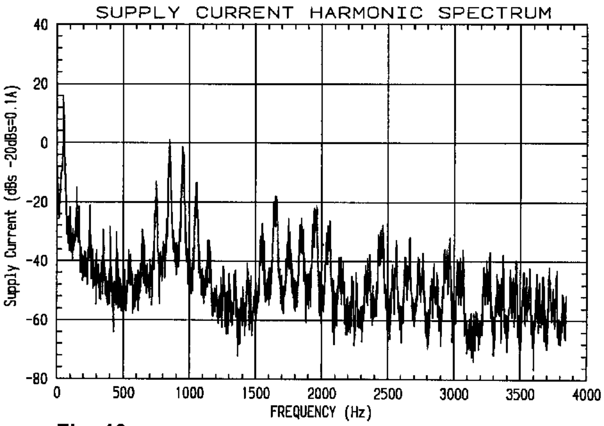

Fig. 10 25kV AC CONVERTER USING RPWM - Load Shedding

5. CONCLUSIONS

The cost penalty of the digital signal processor (DSP) implementation of EPWM has almost disappeared in recent years, these devices now being commonplace in traction applications. Thus, EPWM is a cost effective feedback solution to many ac railway interference problems, particularly narrow band signalling. Its instantaneous demand and output produce very accurate fundamental output voltage, cycle by cycle, whilst the harmonic structure is varying. To combat the possibility of slightly peakier current waveforms, a peak clipping mode was added in practice. This transparently forces extra switching transitions to limit the current without interrupting operation.

With conventional modulation schemes reliance is often placed on converter waveform interlacing to meet signalling and telecommunication interference specifications. The major disadvantage when one converter system fails is that safety requirements might dictate shutting down multiple converters, or switching to an alternative interlacing strategy on the remaining converters. In mass transit systems it can be difficult to reschedule interlacing strategies across vehicles when a converter fails. EPWM need not necessarily depend on interlacing for compatibility. The absence of continuous large fixed frequency harmonics spreads the spectrum, reducing the risk of line resonance and producing less distinct audio noise from converter and transformer.

Hardware tolerances within the converter electronics, which introduce extra unwanted harmonics, become insignificant, with very low dc levels from converter operation in the primary. Simulation has shown an EPWM converter system is more robust to partial dc link filter failure, and that small online switching frequency variations could be made to suit power or thermal conditions within the converter. Self-monitoring could be added using internal analysis to identify potentially hazardous faults in either hardware or software.

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