Trans IMarE, Vol 102, pp 249–259

Harmonic problems and calculation on offshore platforms

***R Yacamini, BSc, MSc, CEng, MIEE and †I D Stewart, BSc, CEng, MIEE**
*University of Aberdeen and †BP Exploration

SYNOPSIS

Large motor drives are increasingly being used on offshore platforms and ships. They are used to drive dc motors, ac induction motors, uninterruptible power supplies, weapon systems and ship dedicated propulsion systems. This paper describes some of the harmonic problems experienced to date on offshore platforms, including the effect of commutation spikes. Methods of calculation are discussed along with the possible excitation of electrical resonances or mechanical torsional resonances. The latter can break shafts. The need to calculate and measure the effects of drives at all stages of the design and development programme of a new platform or ship are discussed.

INTRODUCTION

Very early in the evolution of converters it was recognised that the non-linear nature of the ac/dc conversion produced harmonics in the input waveforms. In addition commutation notches are formed when the two thyristors of a bridge are both conducting, short circuiting the supply in two phases. These aspects have been well documented and different methods recently developed to carry out system analysis.[1,2,3]

The offshore industry has known from its inception that dc drilling equipment has distorted the waveform of the system it was connected to. In early designs of platform systems the drilling equipment was often connected to a system in isolation from the rest of the platform, and also one that utilised diesel generators. Although the harmonic distortions were high the effects were not relevant to the rest of the platform. With the ever increasing drive to find more economic ways to develop so called marginal fields, it is no longer possible to find the space or to support the weight of stand alone generators. In addition the earlier platform design often had large pumps with their own gas turbine drives so that the electrical power system would typically have generators of a few MW in rating. Space, weight and increased maintenance costs resulted in electric motors becoming the norm and typically the generator size increased to 15–25 MW. The offshore power system is similar to marine applications in that generation and motor loads are closely coupled both electrically and physically. This has resulted in system fault levels being relatively high, typically 30–50 kA rms. As has been shown in a previous paper,[4] this fact helped reduce the effects of the harmonic distortion. Further pressure on cost has resulted in a review of sparing philosophies being applied to generators. Systems which would have been 2 x 100%; 3 x 50% or 4 x 33% etc, are now often only 1 x 100%; 2 x 50%; or 3 x 33% etc. Also, single train operation for the process plant is likely to become standard for some future developments. Fault levels therefore are tending to fall.

For some older platforms and oil fields the declining oil production has meant that additional equipment is being installed to increase the production rates and thus total recovered oil from the reservoir. One such field is Forties which has been in production since 1975 and has already passed its peak. Originally there were four separate platforms. In 1987 a fifth platform was added to the South East part of the field which had no generation installed and is therefore connected by subsea cables to the nearest two platforms. The decline in reservoir pressure and the difficulties of maintaining production with just water injection into the reservoir has resulted in the need to consider and use alternative methods of oil production. These methods of artificial lift, as they are called, are becoming an increasing feature of offshore platforms. One method uses electrical submersible pumps (ESPs), installed down the well (5–8000 ft deep). Because of the difficulties in measuring productivity from the wells it has been found beneficial to use

R Yacamini is currently a senior lecturer in the Department of Engineering at Aberdeen University. His previous experience includes 10 years as a design engineer with English Electric and GEC in the rectifier and high voltage dc transmission fields. During this time he made extensive use of physical simulations for controller design and system studies. This industrial period was followed by five years as a lecturer at UMIST where he carried out research, using frequency domain computer programs, into hvdc and reactive compensators. He took up his present post at Aberdeen in 1982 and has been involved in consultancy work for the oil industry for most of this period. The main thrust in his research has been to develop time domain CAD analysis packages for power electronic applications. The work is currently being sponsored by BP and the MoD. He has published over 40 papers in this and related fields.

I D Stewart is currently Head of Electrical Engineering at BP Exploration's Aberdeen Office. He started in industry with BICC at their supertension cables plant and following some 5 years working for consultants he joined BP in 1980. He has worked on many oil petrochemical projects in the UK and overseas. He was responsible for the Ula Field development, in the Norwegian Sector of the North Sea, from concept through to commissioning. He moved to his present position in 1985. Mr Stewart has been involved with the problems of harmonics for a number of years, particularly as the Forties platforms are having additional power electronic equipment installed. In 1989 he was appointed a Visiting Industrial Professor at the University of Aberdeen.

variable speed drives (VSDs) for these pumps. At the moment Forties Echo has 10 VSDs feeding ESPs. The significant aspects of the electrical system are shown in Fig 1. At the design stage it was predicted that harmonic levels under worse case conditions would be significant. Recently measurements have been made of the levels of distortion that will be seen. With the bus section on Forties Echo closed, the predicted levels for 10 VSDs in operation, with one workover, is 12% and 7.5% for Echo and Alpha respectively.

In 1991 an alternative method of artificial lift is being installed on Alpha and Delta and this will consist of 2.2 MW gas compressors fed by variable speed induction motors. Recognising the high levels of harmonics already existing in the system it was decided to use 12 pulse converters to reduce the lower order harmonics. However even with this precaution present, predictions show the total harmonic distortion (THD) rising to 15% on Echo.

There are no regulations that limit harmonic distortion levels on offshore platforms and the guidance used comes from the Electricity Council Engineering Recommendation G5/3 which basically limits distortion to 5% at the point of common coupling. With this background of expected levels it has been recognised that better methods of predicting harmonic distortion and more accurate methods of modelling are essential for the future understanding and design of power systems, both for green field sites and modifications to existing platforms. These are discussed later in this paper.

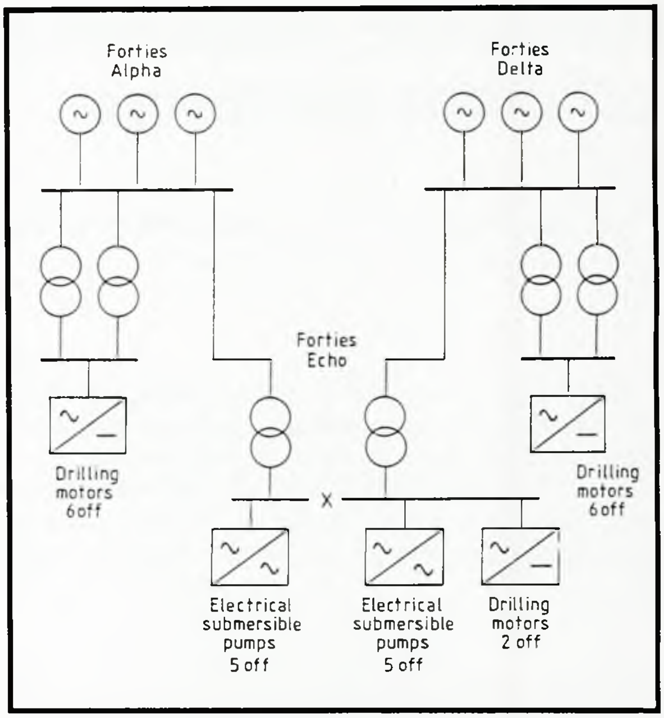


Fig 1: Single line diagram of the Forties field electrical network

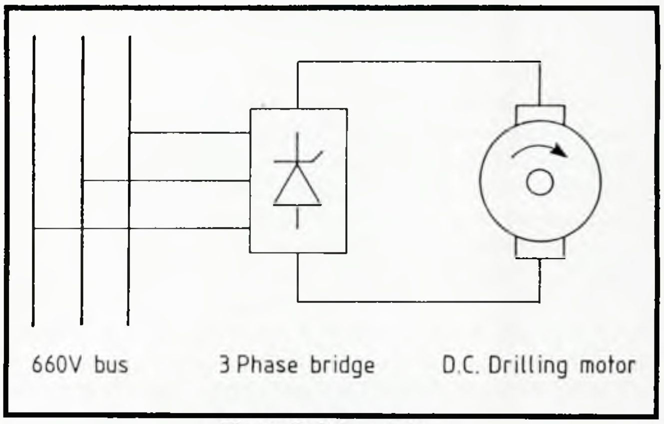


Fig 2: Drilling drive

SOURCES OF HARMONICS

In the context of this paper the word harmonic is used as a generic term to cover all frequencies other than the fundamental supply frequency of 50 or 60Hz, which is used on all offshore platforms and most ships. For the purposes of understanding and analysis of the problems which they cause, such frequencies can be subdivided into three groups. These are the normally expected integer frequencies in the range 150 Hz up to say 1.25 kHz (3rd to 25th harmonic); the higher frequency effects due to fast switchings within the system (in the range 2–50kHz); and lastly, non-integer frequencies in the range dc to a few kHz caused by the interharmonic coupling through variable speed drives. Each of these categories, it will be shown, can cause different problems.

Integer harmonics (150Hz to 1.25kHz)

The predominant source of integer harmonics on offshore platforms and ships is the three phase, six pulse bridge. On platforms this is used for several purposes, such as controlling the dc motor which is used for drilling, and can have a rating of several MW.

Other uses are to supply uninterruptible power supplies, their use as automatic voltage regulators and increasingly as the front end of a variable frequency drive, such as used in gas compression or downhole oil pumping for artificial lift. A simplified diagram of a drilling motor supplied by a bridge from a 660V ac bus is shown in Fig 2. When the bridge is fed from a supply whose impedance is included along with the impedance of the step down transformer, the waveshapes of Fig 3 are produced. There are two features of interest. The first is the fact that a non-sinusoidal current is drawn from the supply. It is this non-linearity which leads to the integer harmonics. These can be calculated using Fourier analysis and can be shown to be of the order of $n=6k\pm1$ where k is an integer. For many purposes the amplitude of the harmonic currents can be calculated using the simple equation $I_n=I_1/n$ where n is the harmonic order and I_1 is the fundamental current drawn by the drive. The basic theory can be found in a standard text such as Ref 5. Unfortunately one of the exceptions to the above simple rules is the dc drilling rig used offshore. In this system the reactance on the dc side of the bridge is very low, which means that there is a six pulse ripple on the dc current which is reflected through onto the ac side as shown in Fig 4. The effect of this ripple is to enhance the 5th harmonic and to reduce the 7th harmonic. A typical frequency spectrum is also shown in Fig 4. For purposes of design it is best to assume that the 5th harmonic component (which is often the dominant component) can be up to 33% of the fundamental current.

Increasingly, VSDs are being used on offshore platforms to run downhole pumps, gas compressors, fans and processing motors. On ships, VSDs are being used on similar systems and also on many weapon systems, which are increasingly making

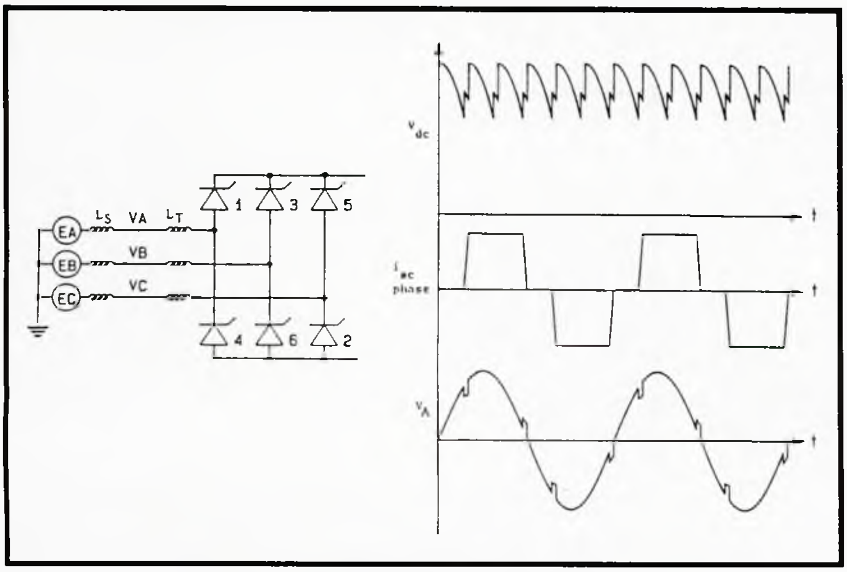
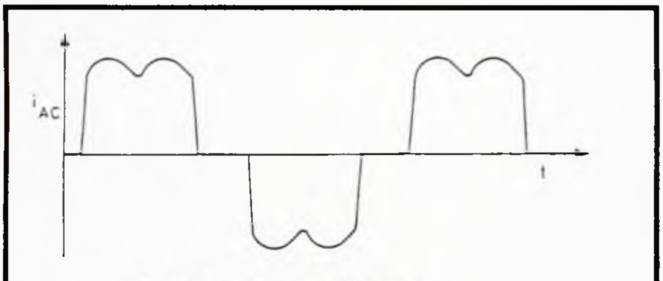


Fig 3: The three phase six pulse bridge



Phase current in practical DC drive

Spectrum of phase current in practical drive (with non-infinite DC side reactance)

Fig 4: Current in a drilling drive (no fundamental shown)

use of controlled ac motors. Every time a new drive is introduced the potential for harmonic problems is increased.

Commutation spikes (2kHz to 50kHz)

Every time a thyristor is fired in a three phase bridge a short circuit of the platform supply takes place. This is illustrated by Fig 5. If thyristor 1 was conducting and thyristor 3 is fired, a short circuit is formed until thyristor 1 is extinguished by the circulating current. This phenomenon known as the 'commutation notch' which this causes on the supply voltage, has been well known for sometime. Another feature of the commutation is that it can excite the natural frequency of the ac system which is made up of the normal system inductances and the cable capacitance, the latter being a particular feature of offshore platforms. A simplified diagram of the waveshapes expected are shown in Fig 6. To show that this phenomenon of commutation spikes does occur in practice the oscillogram (Figs 7a and 7b) shows the bus-bar voltage at the 6.6 kV level on the Clyde platform whilst drilling is taking place. This is heavily distorted and can interfere with other users through this, the point of common coupling (pcc). A more detailed analysis of the commutation notch phenomenon can be found in Ref 4. The larger, high frequency spikes associated with the 660V ac bus feeding the drilling motors is also shown.

Commutation notches have been measured on every platform with which the authors have been associated. On the high voltage bus-bars they are normally in the frequency range of 5–15kHz. On the low voltage busbars (normally around 600V), which supply the drilling converters, the spikes can be in the range 15k–50kHz. They can be looked upon as having two disturbing properties which cause overvolting of all platform equipment and disrupt platform equipment. These are discussed in the section on problems caused in the system below.

Interharmonic frequencies (dc to kHz)

A variable speed drive is made up of three major components. These are illustrated in simplified form in Fig 8. They are the rectifier, the inverter and the motor which is being driven at variable speed. The rectifier and inverter are joined through the dc link (which often gives this type of converter its name). A re-examination of Fig 4 shows that the voltage on the dc side of the rectifier has a ripple which will contain the 6th and 12th harmonics (of the supply which is feeding it). This can cause a ripple current on the dc side at these frequencies. These frequencies will pass through the inverter and will give a source of frequencies into the motor other than the 'theoretical' frequencies described in the section on integer harmonics above. An explanation of how these frequencies, which are called interharmonics, can be calculated using modulation theory is explained in Ref 6. In this paper it is shown that harmonics of the order of:

$$n = (6k_2 \pm 1)f_2 \pm 6k_1f_1$$

can be predicted. In this formula k_1 and k_2 are integers; f_1 is the frequency of the ac supply and f_2 is the frequency which is being provided at the motor terminals. To show that this algorithm will allow calculations to be made on an actual drive, an example is given in Fig 9 of the current spectrum measured on a large fan drive.[7] Most of the predicted interharmonics are evident. As will be discussed in a later section these interharmonics are a source which might excite electrical or mechanical resonances in the ac motor.

The formula quoted directly above is for the interharmonics which will be fed into the motor caused by the 6th harmonic from the rectifier. This can easily be extended to include the 12th harmonic ripple from the rectifier.

A similar formula:

$$n = (6k_1 \pm 1)f_1 \pm 6k_2f_2$$

will apply at the rectifier (supply) side. Thus interharmonics as well as the expected theoreticals will flow in the ac system.

There is the possibility that these could excite resonances in the generators on the platform or ship. Note that at least one harmonic is at a frequency below the fundamental and is non-integer. This is discussed later.

The type of algorithm described here can be developed for any type of converter be it current fed, voltage fed, quasi-square wave, pulse width modulated, be they six pulse or 12 pulse. All will produce harmonics and interharmonics.

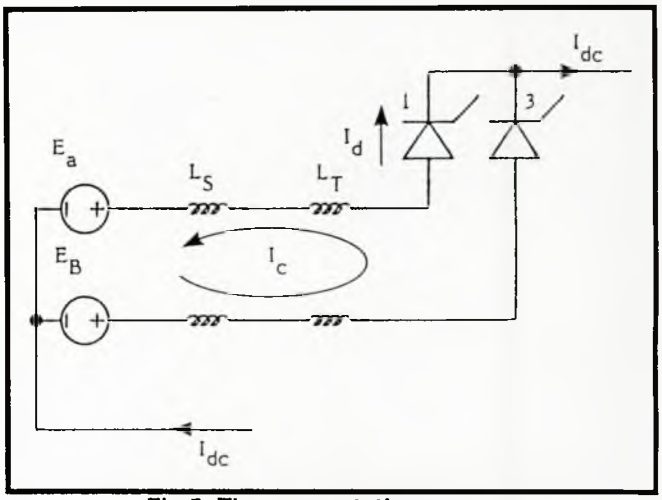


Fig 5: The commutation process

Other sources of harmonics

The sources of harmonics described above are the principal sources measured by the authors to date. Other potential sources are ac machines, transformers, fluorescent light fittings, single phase bridges or indeed any other non-linear circuit involving saturating iron or switching devices. The amplitude produced by such sources is however small and can normally be ignored in most calculations.

PROBLEMS CAUSED IN THE SYSTEM

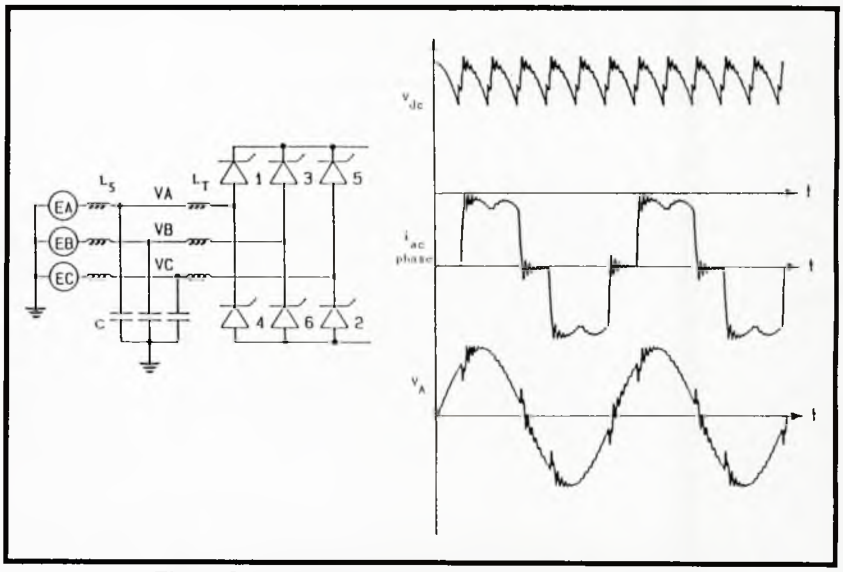


Fig 6: Commutation with a resonant ac system

The problems which have been seen to date or which might be encountered fall broadly into two areas, namely those associated with the upstream and downstream sides of the converter. It has been shown in this paper that these two areas are not independent of each other and some important problems require detailed analysis. The problems generally divide into those resulting from lower frequencies (the harmonics) and those resulting from higher frequencies (the transients).

The problems resulting from lower frequencies are likely to be predominantly heating effects, especially in the rotors of machinery. This is very important to the oil industry where equipment is used in hazardous areas and has been certified on sinusoidal waveforms. Additional heat rise tests are often carried out now, but the effects and estimations of additional temperature rise on other plant have to be treated with extreme caution. Other electrical equipment, such as protection relay and metering, could also be affected. This may not necessarily be unsafe but could be typified by spurious tripping or wrong readings and loss of production.

The types of system that might be affected by commutation spikes are those that rely on a sinusoidal waveform for their operation. Problems have been encountered with automatic voltage regulators (AVRs) giving poor voltage control. Synchronising has been inhibited. Other problems have been with computer systems not being fed from UPS systems, signal wires which are unscreened or incorrectly earthed, control systems on power electronics, overvoltage damaging thyristor equipment, telecom interference, filters on emergency lighting equipment, and in general anything which relies on voltage zero-crossing for its operation. UPS equipment can often have its ability to transfer to the bypass inhibited. Although in itself not critical, there could be severe problems for those systems that rely on the transfer-to-bypass to blow downstream fuses on fault.

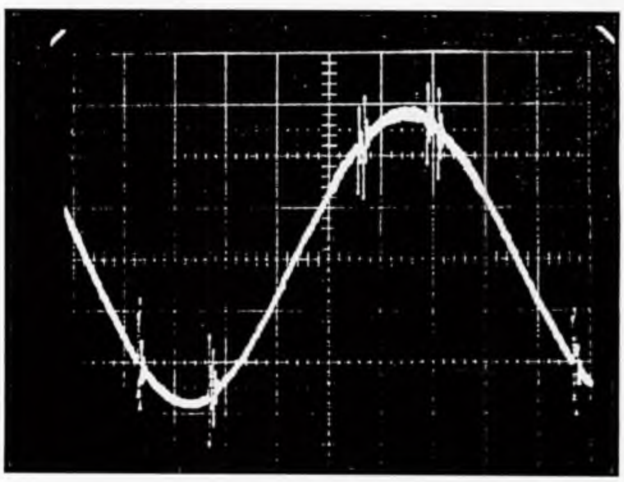


Fig 7a: Commutation spikes on the Clyde platform; 6.6 kV bus voltage

The transient effect of the voltage on the long term integrity of the insulation of equipment is also an area of concern and generally without firm definition. A recent meeting of the IEE machines committee addressed this problem.

Trans IMarE, Vol 102, pp 249–259

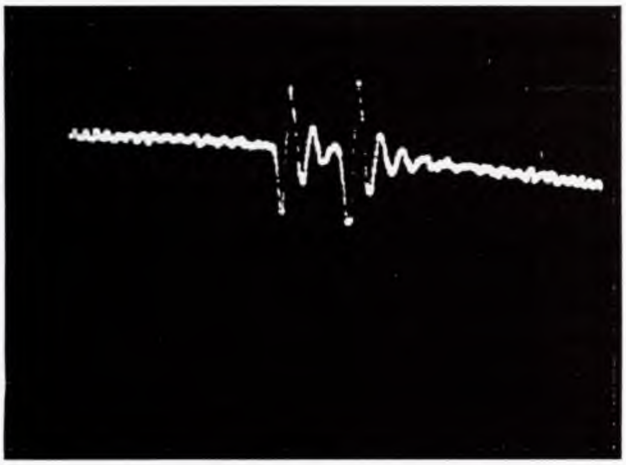


Fig 7b: Commutation spikes on the Clyde platform; expansion of commutation notch

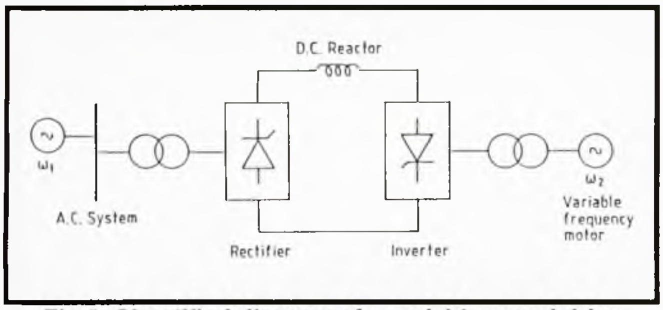


Fig 8: Simplified diagram of a variable speed drive

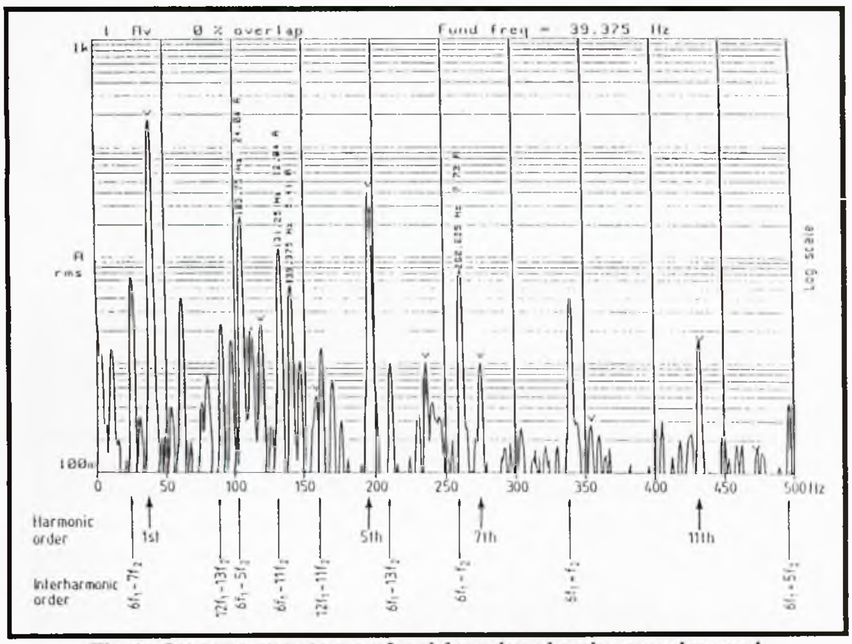


Fig 9: Current spectrum of a drive showing harmonics and interharmonics

The shafts of a motor/pump can be subjected to torsional oscillations which might coincide with a natural frequency that has insufficient damping. A sheared shaft could be the end result. The ESPs that have been installed in production wells have had significant numbers of sheared shafts generally attributed to debris, sand or stuck conditions. There is now reason to question and investigate this problem further. This is discussed in the following section.

MACHINE SIDE PROBLEMS IN DRIVES

In the section on sources of harmonics above it was shown that a very wide range of harmonics can be produced by both three phase six pulse rectifiers and inverters. The harmonics which are produced can in fact range from dc through to tens of kilohertz. In the type of application which is found on offshore platforms and ships, two types of problem can arise which are in addition to the rotor heating and insulation problems described in the previous section. The potential problems are electrical and mechanical resonances.

Electrical resonances on the machine side

One particular example is chosen here for demonstration only. This does not mean that this is the only type of drive which could cause such a problem but it has been chosen only as an illustration. Figure 10 shows a much simplified diagram of a current fed, quasi square wave type of inverter, driving a downhole pump motor. In order to supply the high voltage needed by the pump motor a step-up transformer is used as a supply and a long three phase cable of perhaps 5000 ft in length, to feed the downhole motor. In order to clean up the current waveshape a filter is used on the output of the inverter. If now the equivalent circuit is considered it can be seen that there is a combination of inductors and capacitors which will lead to several electrical resonant frequencies. If one of the harmonics or interharmonics of Fig 9 happens to coincide with one of these resonant frequencies problems can arise which might lead to overvoltages on the cable and the motor. It should be remembered that the spectrum of Fig 9 will vary as f_2 the motor supply frequency is varied. The extent to which this might be a problem will be very dependent on the damping in the electrical system. In carrying out calculations this is often the most difficult parameter to identify particularly as the damping may well be frequency dependent.

Mechanical resonances

The mechanical part of a drive system consists of at least two principal components. These are the rotor of the induction motor machine and the mechanical load in the form of, for example, a fan or a pump. In all such cases the rotational system will form a two mass system. Such a two mass system will have a torsional resonant frequency where one mass will counter-rotate relative to the other. If such a resonance (which is not speed dependent like lateral critical speeds) is excited, then high stress can occur on the shaft. If the stress is high enough to encroach on the fatigue life of the shaft then damage can occur, culminating in the breaking of the drive shafts. To date several occurrences of this kind have been reported in private correspondence to the authors.

To look for the source of such torsional problems it is necessary to turn again to Fig 9. If such a current is present in the stator of an induction machine a harmonic flux will be induced in the air gap which will induce a harmonic current in the rotor. The induced harmonic current in the rotor will interact with the fundamental rotating flux in the air gap B to give oscillating forces on the machine rotor and hence torsional torques. This mechanism is explained in Refs 8 and 9 and illustrated by Fig 11. The combination of the air gap B (from the stator) and the current harmonic on the motor causes the oscillating torque (this is in addition to the steady driving torque). If this then feeds a mechanical system with little damping at its resonant frequency (Q factors of 50-90 are typical), then high stresses and breakages can occur. Problems with downhole pump shaft breakages are reported in Ref 10 where caution is recommended when using pumps with tandem induction motor drives and VSDs. The reasons are not given for this note of caution, but it is thought that the extra power developed by such a motor will place extra torsional stress on the thin shaft used in this unusual motor pump configuration (the total set being perhaps 50 ft long on a common shaft). A study is at present being carried out at Aberdeen University to investigate such problems and to develop a CAD model of the joint electromechanical system.

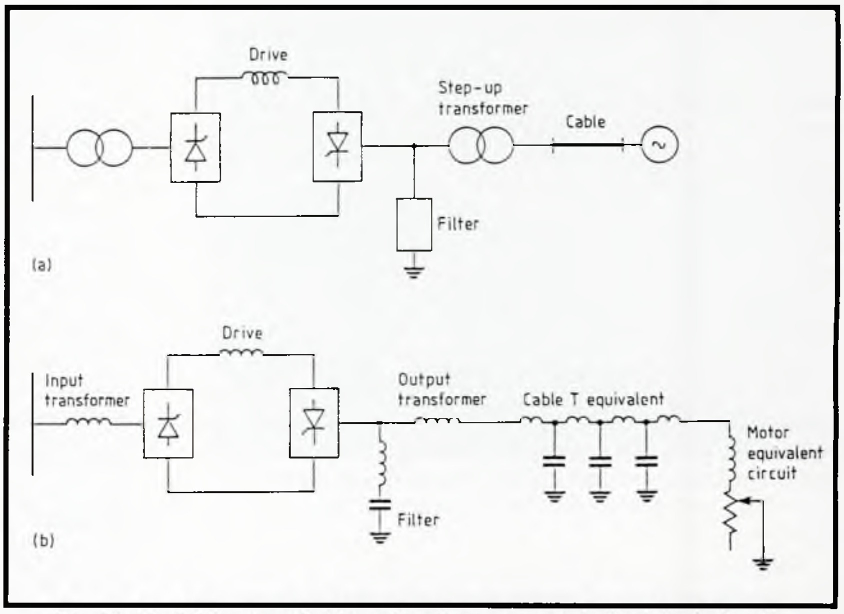


Fig 10: Variable speed drives feeding resonant electrical circuits

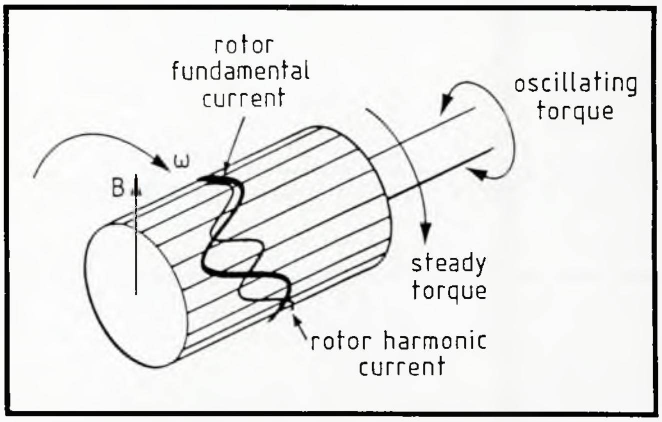


Fig 11: Harmonic currents in the rotor which cause oscillating torques

HARMONIC CALCULATIONS

Calculations at frequencies other than the fundamental can be carried out in three different ways, each of which has advantages and disadvantages.

Harmonic load flows

Computer programs are available which are an adaption of well established power system load flow programs. Programs of this type do their calculations in the frequency domain and as such are cheap to run. For large power systems such as the British Grid System they have much to offer. The harmonic current for each converter is input in tabular form and load flows are carried out. The disadvantages are that such programs will only allow calculations on the ac system to be carried out and also such problems as commutation spikes would not be predicted.

Physical models

The second method of analysis is to build a physical simulator which involves transmission line models, transformer models, converter models, machine models etc. Such models do exist and can be used to calculate harmonics and voltage spikes. Their disadvantage is that they are expensive, inflexible and suffer from high per unit resistance values (it is difficult to get a resistance low enough for high Q resonant circuits). The advantage of such systems is that they provide insight and can incorporate the effect of real controllers.

CAD software packages

The authors have been involved in the use of several software packages which allow the simulation of electrical equivalent circuits to be carried out in the time domain. Several SPICE derivatives have been tried without much success. Such programs do not translate well, from the low power VLSI levels, for which they were designed, to the high power levels necessary to carry out calculations on power electronic circuits and machine equivalent circuits. One program which has been used most successfully is ANDI which is widely available in the university system and is marketed by Silvar Lisco. This lends itself well to power electronic circuit calculations. If more complex circuits, such as three phase cycloconverters, with their associated controllers are simulated, then this package gives very long run times. The large number of nodes slows it down. Also it is not possible to model electromechanical systems. Recently at Aberdeen University the authors have started to use the software simulation package SABER. To date this looks encouraging and will allow a wide range of problems to be simulated including commutation spikes, harmonic load flows and electromechanical systems. Such a system can solve in either equivalent circuit representations or in a differential equation representations or a combination of the two. Initial indications are that it operates considerably faster than ANDI.

GENERAL CONCLUSIONS

The problems associated with harmonics and spikes on small isolated power systems is likely to increase. Such systems can be found on offshore platforms, drilling rigs, semi-submersibles, merchant ships, fighting ships and submarines. The sources of these harmonics are likely to include drilling drives, variable speed induction motor or synchronous motor drives, uninterruptible power supplies, gas compressors, weapon systems, ship electrical propulsion systems and the wide range of power electronic equipment which is increasingly being used in all applications. It is the authors' opinion that in the not too distant future the majority of loads, perhaps as high as 80% on, some small systems will be fed through power electronic systems. There is, therefore, a need for the industry to be aware of the problems so that they can be addressed at the design stage and not be an embarrassing afterthought. It is shown in this paper that both design studies and measurements, during development and commissioning, are required.

The problems which might arise could include the overheating of induction motors; the overstressing of all insulation; the interference with any electronic controller; interference with computers; the excitation of electrical resonances; the excitation of mechanical torsional resonances, which could affect both generators and machine drives, and the increasing trend of all components to 'talk' to each other.

The use of filters is often advocated as a solution to harmonic problems, as is indeed the case. However, the authors would urge caution on the random and indiscriminate use of input filters. Such filters may solve the local problem but by their nature will add further capacitance to the overall system. This may produce, unwittingly, further resonant frequencies which other pieces of equipment can excite, due to harmonics or interharmonics. The general conclusion is that a watchful eye should be kept, by those involved in the overall design of electrical power supplies, on the harmonic content and behaviour of all system components. Harmonic and related studies should be carried out at all stages of design, and the system should be monitored both in the time domain and in the frequency domain at the various sources of construction. If this is done problems can be tackled at an early stage before the system is used in anger.

REFERENCES

1. J C Read, 'High-voltage steel-tank mercury-arc rectifier equipment for radio transmitters', *J IEE*, p 453 (1945).
2. P A T Bevan, 'The application of high-voltage steel-tank mercury-arc rectifiers to broadcast transmitters', *J IEE*, p 469 (1945).
3. W J Bonwick and V H Jones, 'Performance of a synchronous generator with a bridge rectifier', *Proc IEE*,119 No 9, pp 1338–1342 (1972).
4. R Yacamini, L Hu and R A Fallaize, 'Calculation of commutation spikes and harmonics on offshore platforms', *IEE Proc*, Vol 137, Pt B, No 1, pp 35–48 (January 1990).
5. J Arrillaga, D A Bradley and P S Bodger, 'Power system harmonics', Wiley, London (1985).
6. R Yacamini, 'Interharmonics in drive systems', a paper submitted February 1990 to *IEE Proc*, Pt B.
7. D W Grieve and E McShane, 'Torque pulsations in inverter fed induction motors', IEE Conf Publ 310, pp 328-334 (1989).
8. A C Williamson, 'Electrical machines and harmonics', First International Conference on Harmonics in Power Systems, pp 85–102, UMIST (1981).
9. S D T Robertson, 'Torque pulsations in induction motors with inverter drives', IEE Vol IGA-7, pp 318-323 (March–April 1971).
10. T R Brinner, F T Traylor and R E Stewart, 'Causes and prevention of vibration induced failures in submersible oilwell pumping equipment', Society of Petroleum Engineers, Paper 11043, (1982).

Discussion

A D Graham (Hill Graham Controls) I must confess that my Company is in part responsible for some of the harmonic problems that Mr Yacamini and Mr Stewart have been analysing in this paper in that we supplied the high power converters that generate the notches. For years we have had to use complex maths to calculate the harmonics and reconstruct waveforms and I am envious of Mr Yacamini's CAD approach which seems to remove some of the hard work and produces excellent results.

I would argue that problems on the motor side of a frequency changer really are between the motor maker and the inverter supplied and should not normally affect the end user. However, supply side harmonics which affect the entire network in a ship or indeed in a country are most definitely of concern to the marine engineer.

To this end I can offer further examples of real waveforms that we have captured on disc over the last 3–4 years of various systems under different conditions (see Figs 1, 2, 3 and 4). I would argue that the actual harmonic content either expressed in a table or as a percentage distortion factor means less to another user of the supply than a picture of the expected waveform. A table of percentage harmonics can be reconstructed into totally different waveforms by judicious choice of phase angles.

Figure 3 is the 11 kV primary of a 12 pulse system with some source resonance. The dampened oscillation can be seen after each commutation just as shown in Fig 6 of the paper.

Finally, in Fig 4, I include a picture of the 440V bus of a ship with four 1100 kW thrusters in which the four commutation notches are clearly visible.

My question is whether BP or anyone else has actually identified motor insulation failures caused by ringing spikes due to commutation.

R Yacamini (University of Aberdeen) and I D Stewart (BP Exploration) The possible failure of motors, or for that matter any piece of electrical equipment connected to a supply system with severe distortion due to ringing spikes from commutation, is a matter that could be debated for some time. The effect of commutation spikes is certainly more critical for those items of plant that use the waveform and the voltage zero crossing as a reference, eg synchronising. Here the additional zero crossings, seen under certain operating conditions of the drilling equipment in offshore installations, have in the past been problematical. In fact Fig 1 of Mr Graham's contribution shows the effect of commutation giving rise to, or at least being very close to, additional zero crossings. The question as to whether these could also be an added reason for insulation degradation is one that I am unable to answer definitively. Certainly no-one could doubt that the insulation is placed under additional stress which ultimately could lead to premature failure, often seen in the failure of the electrical system. Here the insulation resistance (IR) may start as high as 100 Megohms before installation and drop to as little as 1 Megohms when the pump and cable system has been installed in the well. After some time in operation the IR has sometimes dropped to as low as 50 kohms. For those installations connected directly to the electrical system we would be interested to see if it could be argued that the distorted waveforms, such as shown in Fig 1 of Mr Graham's contribution, would definitely not cause earlier failure than a pure sine wave. We would not be able to make such a definitive statement ourselves.

Dr K McLeay (YARD Ltd) The authors are to be congratulated on their clear exposition of harmonic problems in offshore installation electrical equipment and on the use of modern computer aided engineering software for analysing and predicting the phenomena. Following work at YARD using time domain analysis with CAE packages the following questions are posed to the authors:

1. One of the main effects of distortion in marine systems is on rotating electrical equipment and its associated driving or driven equipment. The authors have mentioned the modelling of these using the SABER package. Can the description of the modelling of electromagnetic interaction between converter produced currents and harmonic torques be expanded a little further, ie is magnetic saturation accounted for and to what extent have the authors found that the accuracy of the machine models affects the system harmonics?
2. Given that validation of such techniques is difficult or impossible on an operational oil platform, have the authors validated the work on a test network? If so how important have they found frequency dependent parameters to be – eg the effect of cable skin, especially where there are cables to other installations?

R Yacamini (University of Aberdeen) and I D Stewart (BP Exploration) The subject of electromagnetic interaction between the converter currents and harmonic torques was not covered in the paper because at that stage we had little experience of modelling such a system. Since the paper was first drafted we have been studying this problem and are now in a position to model the interaction between the electrical and the mechanical systems (in both directions) using SABER. To date we have not advanced as far as introducing saturation effects but we understand that this will be possible if necessary.

The question of how the machine model affects the harmonic currents is one that we are also actively pursuing. To date we have been trying to carry out the calculations using three single phase equivalent circuit models. We now feel that we have to abandon this method because of problems that this causes around current zero, especially for cycloconverter drives. We are therefore now adopting a two axis theory model for all synchronous and induction machine drive and generator models. A recent paper discusses the efficacy of different orders of model (see Ref 1).

In order to test the computer model against a known system we have adopted the approach of comparing it to a laboratory set up whose parameters we can easily measure. In this case we can achieve excellent results. We are also at the moment comparing model results against site measurements carried out on a downhole pump test well at Lasalle, Inverurie, using several different drives cables and motors. The results from this are encouraging. When we have evaluated these more fully we would propose to prepare a paper on the subject at a later date.

J B Borman (Lloyd's Register) The authors are to be congratulated for the presentation of the paper which is on a topic that has not before received adequate attention in the marine literature. The use of thyristor equipment is now widespread in the marine industry and the potential problems that can be experienced have been clearly highlighted in the paper.

On the subject of commutation spikes the recordings shown in Fig 5 illustrate the variation in voltage overshoot at the end of the commutation process for two system operating states in a 600 volt marine installation. These recordings demonstrate that operating conditions do have a significant influence on the magnitude of the overshoot and the stress that is imposed on the insulation system.

Experience with a number of installations has brought a sense of caution when trying to interpret recordings because it is easy to be misled by inadequate recording devices, particularly voltage and current transformers. It has been found necessary, for really reliable recordings, to use voltage dividers that are correctly designed, terminated and tested. My first question to the authors is about the high voltage measuring techniques used for Figs 7a and 7b of the paper. Did they use voltage transformers or voltage dividers, and if voltage transformers, were these the ones already fitted in the switchboard, and what was known about the frequency response of the transformers?

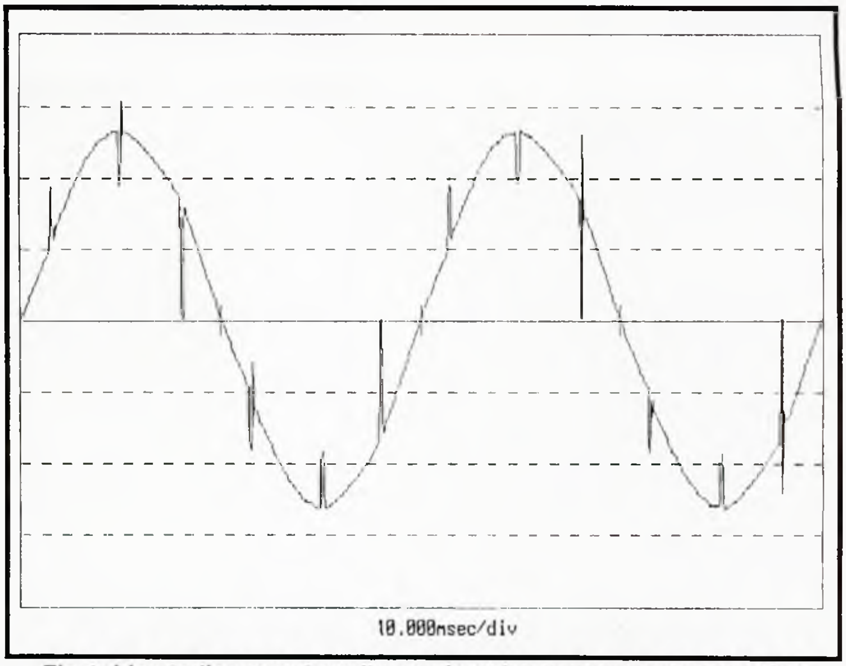


Fig 1: Line to line supply volts on six pulse converter regenerating

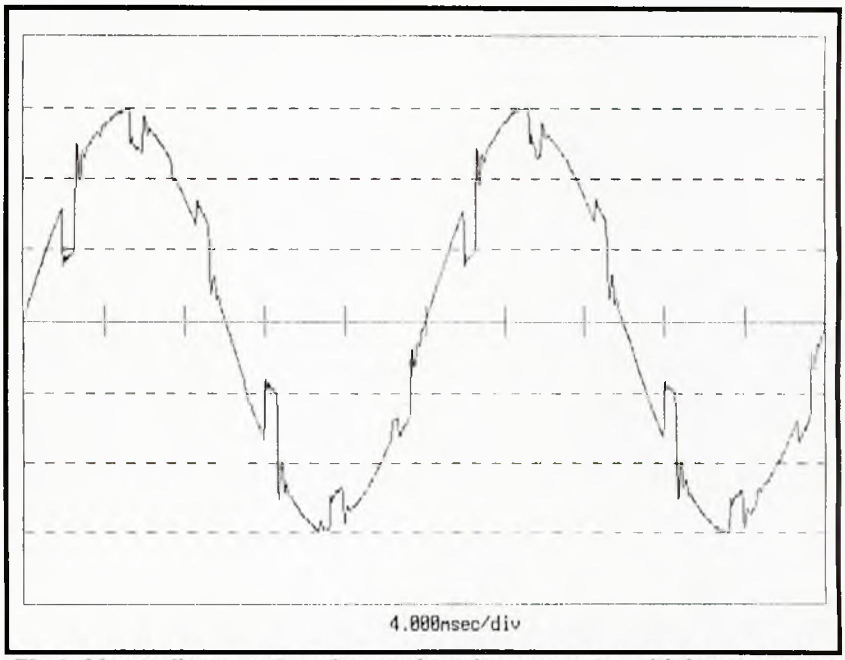


Fig 2: Line to line supply volts on six pulse converter with input reactor

The paper has a number of computed waveforms and some measured waveforms but there appears to be no correlation between the two. I would be interested in the authors' experience of comparing calculations with measurements, particularly with regard to commutation oscillations (or spikes) which are presumably sensitive to parameter variation. Experience of relatively simple installations has indicated that the correlation between design calculations and measurements is not particularly good, although it is satisfactory for the lower harmonic frequencies. For best agreement it has been found necessary to juggle with the value of supply impedance, which on marine installations tends to be dominated by the generators. What have the authors found about selection of machine parameters?

Usually all converter equipment incorporates some snubber and suppression circuits that have capacitors etc. It is not clear whether these have been included in the models.

Fig 9 of the paper illustrates the difficulty of providing a satisfactory filter for an installation that has converters of the ac/ac type. Tuned arm filters that are frequently used for power system filtering are clearly not likely to prove satisfactory and some of the alternatives involve unacceptably high losses. Have the authors developed a satisfactory filter circuit and may one ask what it looks like?

R Yacamini (University of Aberdeen) and I D Stewart (BP Exploration) The measurements on the offshore installation were carried out using the voltage transformers installed in the switchboard. In terms of frequency response there have been no calibration tests carried out but reasonable results to a frequency of at least 1–2 kilohertz are expected.

Where we have managed to compare existing current transformer outputs with modern high band width Hall effect probes, we have found the cts to give a good output in the frequency range encountered.

The question of comparison has been dealt with in the previous reply. On the question of machine parameters we would, wherever possible, use the output from a modern short circuit calculation program which is designed to include generator, and very importantly for offshore platforms, induction motor impedances. This would seem to give the most accurate figure for the commutation reactance between the converters and the Thevenin equivalent emf.

Snubbers and dampers are included in the model.

The subject of filters on systems of this type is a very large subject. To date we have no practical experience on oil platforms of harmonic filters and would advise caution on their use to others. Often filters shift the problem to another frequency. To

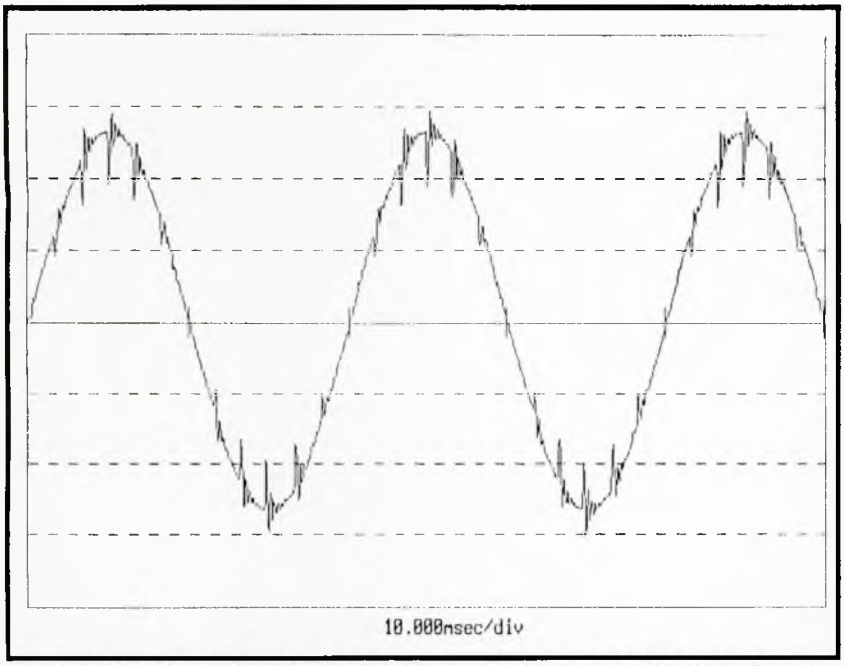


Fig 3: 11 kV line to line volts on primary of transformer feeding 12 pulse 2MW inverter

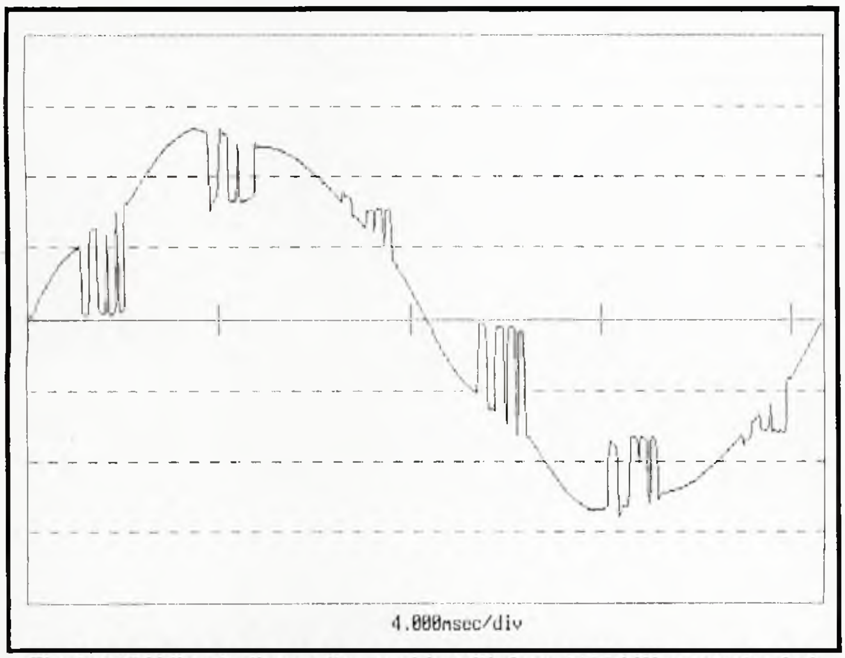


Fig 4: 415 V line to line volts on ship with four 1100 kW converter fed thrusters

solve the problem of commutation spikes the method proposed many years ago (see Ref 2) would still seem to have many advantages.

R H M Hall (Lloyd's Register) I should like to offer some observations regarding two matters touched upon by the authors' most informative paper; firstly, certified equipment for use in hazardous areas, and secondly, commutation.

It is mentioned that additional heat rise tests are often carried out on equipment originally certified for use on sinusoidal supplies. This has certainly been the case with motors intended to run on solid state inverter or converter supplies, but I know of no other instances.

This begs two questions: 'What about equipment other than motors' and, 'what about motors fed directly from distorted supplies?'

In the first case, safety may well be compromised by supply distortion even where properly certified equipment is installed in a proper manner, since the certification will not, almost certainly, lay down any requirement for supply purity. Exe luminaires give, perhaps, the most immediate cause for concern, both because of the known susceptibility to supply distortion of some luminaire components and because (unlike their flameproof equivalents) they may offer no effective barrier between the failed or overheated component and the external atmosphere; however, it is clear that many other types of equipment may be equally susceptible. In the case of motors fed from distorted supplies, overheating or mechanical or electrical failure may be thought unlikely, but the user should note that it has recently become British practice to define the purity of supply required for motors (other than those fed from solid state converters, etc) in terms of Clause 12.2.1 of IEC 34–1 or the equivalent clause of BS4999: Pt 1. These require that the difference between the instantaneous value of the voltage waveform and its fundamental should not exceed 5% of the amplitude of the latter.

Clearly, notching due to converters on the same supply is likely to breach this requirement; the certified motors would not, then, be operated in accordance with their certification documentation, and the user would be 'on his own'; he would, in effect have taken it upon himself to vouch for the continued safety of the motors.

The mention of commutation notches brings me to the authors' treatment of the subject; although the paper is, of course, not intended to deal with such matters in depth, I feel that the non-specialist would be assisted if the authors were to included a brief mention of the factors allowing the reverse current flow through the left hand thyristor of Fig 5 of the paper, and those factors determining the width of the commutation notch.

R Yacamini (University of Aberdeen) and I D Stewart (BP Exploration) The contribution of Mr Hall raises a number of questions on the certification problems of equipment connected to distorted waveforms, which are of great concern in the offshore environment. It would be easy if all the answers were known. The difficulty arises immediately that the levels of distortion, whether in terms of commutation notched, total harmonic distortion, or individual harmonics, have not been agreed by the necessary standards bodies. Motors expected to operate directly on distorted supplies from inverters have additional temperature rise tests carried out on them. It is important to assess what the effect will be on the other equipment connected to the distorted system. For motors connected to a system with harmonic distortions the main concern will be additional heating. I would ask that those manufacturers and researchers working on the design of machines, provide methods that have been agreed to assess the additional effects of heating from harmonics. In the meantime the way in which motors are generally selected is by using end of curve for the pump and by using class F installations, but operated with only class B temperature rise. This should give sufficient margin so that until more definitive ways of calculating the heating effects have been established there is no cause for concern from a certification point of view. Many other methods of monitoring parameters of the critical motors on offshore platforms are under development and these will also aid in the additional safety of the installation. The main cause of concern is directed at Exe luminaires. The problem of harmonics has been mainly found on battery backed units where input filters have acted as short circuits to the harmonics such that fuses have blown. These fuses were part of the encapsuled components and did not give cause for concern on heating but meant that they had to be replaced, including the associated rectifier/inverter. The cost to do so was high.

Much of the equipment susceptible to the commutation notch is, in fact, in the electronics used within control, monitoring and protection devices, and as such is generally placed in non-hazardous areas of a plant. There, no certification problems arise.

The continuing quest to be able to design properly the power system, including the different harmonic distortions, will allow standards to include the correct restrictions whether for operational or certification needs. The authors hope that the work they have been involved with will assist in this aim.

A fuller treatment of commutation notch terminology can be found in Ref 3. The reverse current indicated in Fig 5 of the paper is in fact only a component of the current. The actual current is the sum of the dc current and this component. The width of the notch increases with increasing dc current, increases with increasing ac side reactance and decreases with increased firing angle.

Fig 5: Voltage waveforms on ac systems with converter load

Lt Cdr M Murphy (MoD Procurement Executive) The Ministry of Defence (Royal Navy) is currently considering the option of a full electric propulsion system as an alternative to traditional mechanical drives for the next generation of surface warships. In addressing the relative advantages and disadvantages of the available systems, a principal concern for an electric drive centres on the harmonic disturbances caused by the drive converter in two respects. Firstly the downstream effect of distorted supplies on the propulsion motor and consequent transmission of electrically induced noise to the sea, and secondly the quality of supplies reflected onto the ships supply busbars upstream of the converter. High quality supplies with low total harmonic distortion are paramount for computing and weapons systems.

Many parallels can clearly be drawn between offshore platforms and ship propulsion systems, and hence this paper presented by Mr Stewart and Mr Yacamini is of great interest. Whilst the MOD are actively researching such harmonic problems, and ideally seek a solution at source (ie minimise distortion levels by careful design of the drive), clearly BP have been unable to do such as the variable speed drives have appeared as 'add-ons' to their platform equipment over the life of the platforms. My question to Mr Stewart is how are BP proposing to deal with distortions levels cited as being as high as 30% in worst case conditions?

R Yacamini (University of Aberdeen) and I D Stewart (BP Exploration) The distortion levels on the Forties platforms are of concern or we would not have embarked on the different ways to evaluate and measure the levels seen in practice and predictions for the future. The levels of 30% are a very rare short time peak and therefore can be ignored for heating effects. In the case of insulation failure there is insufficient known currently to quantify such effects. The general levels of distortion that the system will be allowed to rise to will not exceed 15%. At this level we are confident that the known problem areas will be under control. Nevertheless we are not underestimating the potential for other problems to become evident with such levels of distortion. We will be keeping a close watch on the system in the future and as part of any assessment on failures, operational problems etc, the aspect of harmonics will now have to be evaluated.

We have designed theoretical filter systems to reduce the harmonic levels to more conventional levels. We are still pursuing manufacturers to provide such equipment that can be installed on an offshore installation. On future installations we will consider the use of equipment that distorts the waveform less, eg 12 pulse rectifiers etc.

References

1. G K M Khan, D F Davidson and L Lixin, 'Some aspects of the electromagnetic design of a converter fed high speed synchronous motor', IEE Conference Publication No 310, pp 215–219.
2. P A T Bevan, 'The application of high voltage steel tank mercury-arc rectifiers to broadcast transmitters', *JIEE*, p 469 (1945).
3. E W Kimbark, *Direct Current Transmission*, Vol 1, Wiley Interscience, pp 80–83 (1971).