# JET Fusion experiment 36 kV enhancement studies

K.S. Smith CEng MIEEE

**Abstract: The electrical pulsed power loads at the Joint European Torus (JET) fusion research facility have increased since operations began in 1983. As a consequence the transient voltage swings on the three 36 kV switchboards during JET pulsing are unacceptably large on occasion. This paper describes the use of the PSCAD-EMTDC program to determine the improvement in the system performance that would be possible by reconfiguring the system. A transient load flow model demonstrates that operating the incoming transformers in parallel improves the voltage regulation. Parallel operation increases the prospective fault currents to levels that exceed the ratings of the existing 36 kV equipment. Pyrotechnic fault current limiters (FCLs) are proposed to overcome this. Models are developed for the FCL tripping logic that is based on instantaneous current and rate of change of current measurements. Studies confirm that trip settings can be selected for the FCLs so that they will not operate incorrectly when switching the largest converter transformers or the reactive power compensation capacitors. An aggregated load model in which the transient load demand on each 36 kV switchboard is represented by two thyristor converters is described and used to assess the stability of the FCL solution to the transients produced by the JET pulsed power load. On the basis of these simulation studies the better overall engineering solution compatible with the unique characteristics of the JET loads can be identified.**

Keywords: Fault Current Limiter, Joint European Torus, JET, PSCAD-EMTDC, pulsed power, short circuit, tokamak

## I. INTRODUCTION

The Joint European Torus (JET) facility, at the Culham Science Centre, Oxfordshire, UK, is operated by the United Kingdom Atomic Energy Authority (UKAEA) on behalf of EFDA (European Fusion Development Agreement) and is the world's largest experimental magnetic confinement nuclear fusion research tokamak [1]. Construction began in 1978 and it has been operational since 1983. JET became the first experiment to produce controlled fusion power in 1991 and in 1997 operations included successful experiments using mixed deuterium-tritium fuel reaching a record 16 MW of fusion power. Experimental work at JET is now focused on developing systems essential for the implementation of the International Tokamak Experimental Reactor (ITER) to be built at Cadarache in Southern France. This experimental program places increasing transient pulsed power demands on the electrical power supplies, necessitating an upgrade to the existing 36 kV JET switchboards.

This paper outlines the unique characteristics of the pulsed power JET load and describes transient computer models developed using the PSCAD-EMTDC program. The models were used to assess different design options for the proposed JET 36 kV Enhancement program.

## II. JET ELECTRICAL SYSTEM

The power supplies for JET are derived from the UK's 400 kV, 50 Hz transmission system. Three 36 kV switchboards BB101, BB201 and BB301 are supplied by three dedicated 400/36 kV, 90/300 MVA (continuous /pulse rated) incoming transformers SGT1A/B/C as shown in Fig. 1. The link between BB101 and BB301 provides maximum flexibility in the event of a transformer or switchboard outage.

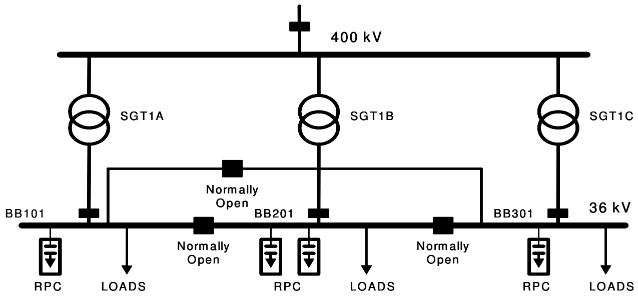


**Fig 1 SLD of existing JET 400 kV and 36 kV systems**

Interlocking is provided to ensure that two or more incoming transformers cannot be operated in parallel to avoid excessive fault levels. The loads supplied from the three 36 kV switchboards are pulsed loads associated with the JET fusion experiments. These include outgoing circuits to the fly-wheel-generator converter sets, supplies for the toroidal and poloidal magnetic field coils as well as supplies for plasma heating systems. Each of these loads is supplied via converters with front end input transformers and thyristor rectifiers. Four Reactive Power Compensation (RPC) units are also connected at 36 kV. A description of the initial design of the JET electrical system is given in [2] from which the contractual limits of the JET load on the 400 kV power system are reproduced in Table 1. This indicates the pulsed nature of the JET load with power swings as fast as 200 MW/s and individual step changes in load of up to 75 MW being allowed with the maximum grid intake capped at 575 MW.

**Table 1 – 400 kV power system characteristics at JET** [2]

| | | |
|---|---|---|
| Local prospective fault level | 15,000 - 35,000 MVA | |
| Max grid permitted voltage step | 1% | |
| Maximum pulse power | 575 MW | |
| Maximum change in power | 200 MW/s | (0 to 200 MW) |
| | 60 MW/s | (200 to 575 MW) |
| Power steps | 50 MW | (SC <20,000 MVA) |
| | 75 MW | (SC >30,000 MVA) |
| Maximum energy per pulse | 15 GJ | |
| Harmonic distortion limit | 1.50% | |

---

Dr K.S. Smith is with Mott MacDonald, Transmission and Distribution Division, 1 Atlantic Quay, Broomielaw, Glasgow, G2 8JB, UK. (e-mail: Kenneth.Smith@mottmac.com *or* Kenneth.Smith@ieee.org)

**Presented at the International Conference on Power Systems Transients (IPST'07) in Lyon, France on June 4 - 7 2007, Paper No IPST07-82.**

Additional loads have been added to each of the three JET switchboards since the facility became operational. Future developments will further increase the total load [3] such that during JET pulsing the transient voltage dip on the 36 kV system can be unacceptably large. The aim of the JET 36 kV enhancement program is to improve performance by reducing the problematic transient voltage dips during pulsing and so increase the robustness of the power supplies to the JET experiment.

## III. TRANSIENT LOAD FLOW MODEL

The loading on the 36 kV JET system undergoes extreme step changes and rapid MW and MVAr swings during JET pulsing activities. A typical JET pulse has a total duration of 90 sec, with most demand on the electrical supplies occurring between 30 and 60 sec. As a conventional load flow model cannot be readily developed to study this phenomena, a PSCAD-EMTDC "transient load flow" model was developed to study the dynamic performance of the system during JET pulsing.

By examining historical data the JET pulse which had previously produced the maximum demand for each outgoing 36 kV circuit was identified. For this pulse the corresponding time variation of the circuit MW and MVAr demands was obtained from the onsite Control and Data Acquisition System (CODAS). The CODAS data streams are time synchronised to the beginning of each individual 90 sec JET pulse and in text format, which could be read into PSCAD-EMTDC. Within the model the CODAS data streams and estimated demands for future loads are summed to give the total time varying MW and MVAr load demand per 36 kV switchboard, i.e. Pd(t) and Qd(t). The loads are modelled by time varying impedances which are continually updated during the simulation using the demand and voltage feedback signals. This approach gives an inherently pessimistic estimate of the future maximum JET pulse which would produce the largest voltage depressions on the 36 kV switchboards.

The four RPC units (each nominally providing 50 MVAr at 33 kV) are switched to boost the 36 kV system voltage during JET pulsing. Different RPC switching schemes were considered including switching units at specific times during the JET pulse and also switching units "single shot" under voltage control.

A number of different factors both internal and external to JET influence the transient performance of the system; these are the pulsed loads of JET itself, the tap settings on the incoming 400/36 kV grid transformers, and the grid Thevenin equivalent voltage and impedance. The model was used to predict the system performance during the future worst case JET pulse without implementing any changes to the existing system. Typical traces obtained from one of the studies are shown in Fig. 2 for the case with a weak 400 kV grid (minimum fault level) and the transformer taps set for an initial voltage of 34.5 kV (the normal operating condition). The peak demand occurs during the period t=30 to 60 sec when the system voltage depression is the greatest. In this particular case, three of the 50 MVAr RPC units (one on each switchboard) are switched in at t=25 sec and switched out at t=60 sec which accounts for the step changes in the switchboard voltages at these instants. The 4th 50 MVAr RPC unit on BB201 is switched "single shot" under voltage control and switches in at t=41.7 sec when the voltage falls below the threshold value of 33.227 kV and out at t=53.4 sec when the voltage recovers to 36.00 kV. The minimum retained voltage on each switchboard is listed in Table 2. Good agreement between predicted and observed measurements with the existing 36 kV system configuration was obtained. On BB101 and BB201 the retained voltage is above 32.0 kV, however the regulation on BB301 exceeds 12 % when the voltage dips to 30.24 kV. If JET were to loose the single RPC unit on BB301, studies show the voltage would drop even further to 28.46 kV at which point the JET equipment would suffer a significant reduction in performance, or may even trip out. This would be detrimental to the experimental program at JET.

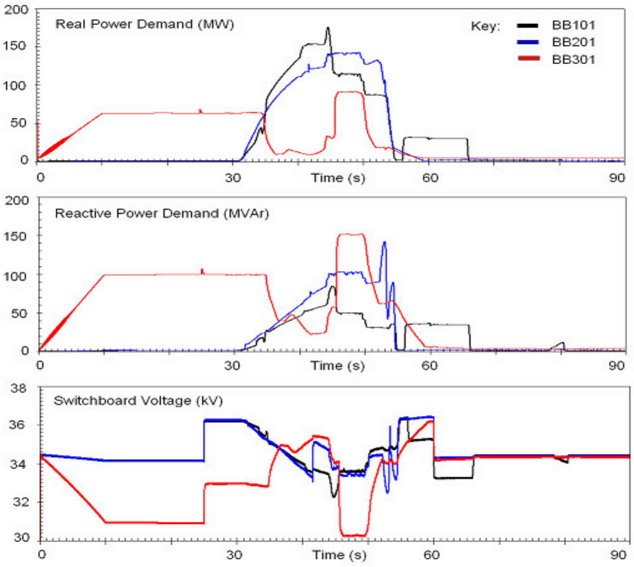


**Fig 2 PSCAD-EMTDC predicted 36 kV load flow quantities for future worst case JET pulse with existing system configuration (t = 0 to 90 sec)**

**Table 2 Predicted minimum switchboard voltages (based on "analogue" metering calculation with 20ms time constant)**

| Switchboard | Minimum retained voltage | | | |
|---|---|---|---|---|
| | Existing arrangement | | Proposed arrangement three parallel transformers | |
| | (kV) | Reg. (%) | (kV) | Reg. (%) |
| BB101 | 32.32 | -6.32 | 32.44 | -5.97 |
| BB201 | 32.53 | -5.71 | 32.44 | -5.97 |
| BB301 | 30.24 | -12.35 | 32.44 | -5.97 |

Note : Initial voltage on 36 kV system is set to 34.5 kV

Further studies were carried out to assess the improvement in the system voltage regulation when operating all three incoming transformers in parallel. The studies showed that sharing the load between the three transformers would ensure an acceptable minimum voltage on each switchboard. For example, as shown in Table 2 the minimum retained voltage is increased to 32.44 kV - a considerable improvement on the previous value of 30.24 kV predicted on BB301. With parallel operation of the incoming transformers loss of an individual RPC unit will be operationally less severe than at present. Studies confirm that with three RPC units the voltage on each switchboard remains above 31.5 kV.

## IV. FAULT LEVEL ISSUES

The impedance of each of the 400/36 kV grid transformers is ~23 % (on 300 MVA pulse rating). At 36 kV this gives an asymmetric peak current contribution of the order of 45 kA per incoming transformer. As the downstream JET loads are supplied via converters they do not provide a fault current contribution. The switchboards are rated at 2500 A with a bus-bar short circuit capacity (symmetrical) of 31.5 kA for 3 s. The circuit breakers have an interrupting capacity of 31.5 kA symmetrical rms and a make rating of 85 kA. With two and three grid transformers operating in parallel, the prospective asymmetric peak make currents exceed the circuit breaker make ratings by 5 % for two transformers and by 58 % for three transformers. This is why inter-locking has been applied to prevent two or more incoming transformers being operated in parallel. Single phase faults are not an issue as the star connected secondary winding of each 400/36 kV transformer is earthed via a neutral earthing resistor which limits the transformer's earth fault current contribution to 20 A.

The "transient load flow" studies show that operating the incoming transformers in parallel improves the voltage regulation on the 36 kV switchboards, however the rating of the existing switchgear prevents this from being allowed. One potential solution to overcome the limitation of the existing equipment ratings and allow parallel operation of the incoming transformers is to use fault current limiting devices.

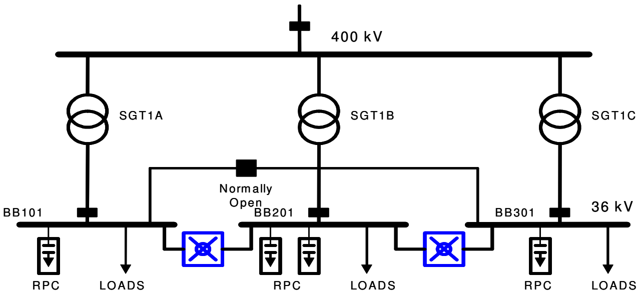
## V. FAULT CURRENT LIMITERS

Fault current limiters (FCLs) have been widely applied in industrial systems, where system expansion has resulted in the prospective fault current exceeding the fault duty of existing equipment [4 - 7]. Commercially units are available up to 36 kV with continuous ratings of 2500 A (156 MVA) and an interrupting capacity of 140 kA (rms) [8, 9]. They are designed to separate parts of an electrical network when a fault occurs. They must operate very quickly to prevent the fault asymmetric peak current exceeding the make rating of the system equipment, i.e. the limiter must detect a fault and operate within the first few milliseconds of a fault. The decision to operate/trip the limiter is made on the basis of instantaneous current and rate of change of current (di/dt) measurements. The operational part of the limiter comprises a current limiting fuse in parallel with an explosible link. The tripping logic causes the link that carries the normal load current to be detonated and thus ruptured, so commutating the current into the parallel fuse that then operates breaking the fault current. After operation, the FCL is isolated and inserts containing the fuse and the ruptured link are removed and replaced. One device is installed in each phase of a three phase system, and a circuit breaker is required in series with the FCL to inter-trip the remaining phase(s). The circuit breaker also provides a downstream isolation facility.

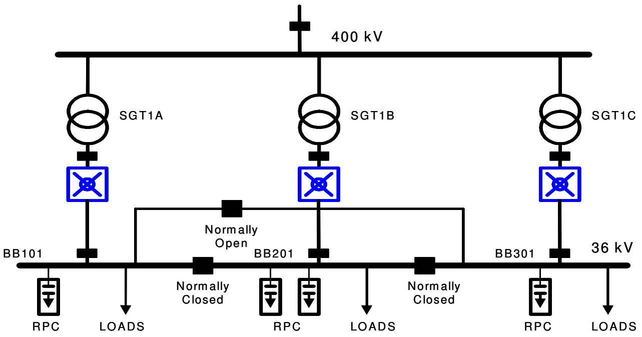
Fault current limiters therefore provide a low impedance connection during normal operation, and in the event of a fault occurring rapidly split the network so that the currents flowing through the circuit breakers or switchboards do not exceed their fault ratings. Such FCLs could provide an ideal method of inter-connecting the existing 36 kV JET switchboards to achieve the desired improvement in the system voltage regulation during JET pulsing. The following sections describe different scenarios investigated using PSCAD-EMTDC simulations to assess the suitability of FCLs for this unique application.

## VI. DESIGN OPTIONS

Two design options are possible for the JET installation as shown in Fig. 3. In Option A, two FCLs are placed between the existing switchboards. In the event of a fault, depending on the fault location, operation of one or both units will limit the peak asymmetric fault current to that supplied by a single incoming transformer. In Option B three FCLs are used; one placed in series with each of the incoming 400/36 kV transformers. A three-phase, or phase to phase fault occurring at any location on the 36 kV system would cause all three FCLs to operate rapidly thus disconnecting all sources of fault current. With this arrangement the fault current passing through the incoming transformers is limited, giving them added protection by not exposing them to the full short circuit current and this is of advantage to JET.



Option A – Two fault current limiters



Option B – Three fault current limiters

**Fig 3 Design options for installation of fault current limiters**

The "transient load" flow model was used to determine the maximum rms current flowing through the FCLs as follows:

| | |
|---|---|
| Option A | 1600 A |
| Option B | 2250 A |

Allowing for the duration of the JET pulse and the elapsed time between successive pulses, these currents were used to identify the required thermal ratings of the FCLs.

## VII. FCL TRIPPING CRITERIA

Tripping criteria based on current magnitude and di/dt measurements were calculated for both installation options, based on the fundamental frequency fault current waveshape taking into account waveform asymmetry. The selected trip settings were 4.86 kA for the instantaneous current magnitude and 3800 kA/sec for the instantaneous di/dt. When both of these levels are exceeded simultaneously the FCL should operate. These settings apply to both design options.

FCLs and their tripping logic were implemented in the PSCAD-EMDC model using the methodology described in an earlier paper [10]. Within the model the explosible link of the FCL is represented as a current chopping switch; when opened this commutates the current to a parallel variable resistance whose value is initially small, becoming larger with time to mimic the action of the fuse element blowing. Simulations for both design options showed that the selected tripping criteria produced correct operation of the FCLs for three phase and phase to phase faults at any point on the 36 kV system.

The stability of the FCL tripping logic was assessed for individual switching operations associated with the capacitive RPC units. Analysis of Fig 4 shows the 50 MVA RPC units are damped harmonic filters nominally tuned to the 5th harmonic. The 12 Ω damping resistor decreases the time taken for the steady state current to be reached but it does not significantly change the initial di/dt. As an example, for Option B, PSCAD-EMTDC studies showed that the peak instantaneous current flowing through the FCL was 1.39 kA with the di/dt reaching a maximum value of 7805 kA/sec. The peak current is 29% of the FCL magnitude trip setting and the di/dt is 200% of the setting value. As both magnitude and di/dt levels must simultaneously exceed 100% before the FCL operates, it was concluded that the selected trip settings are stable for this transient event.

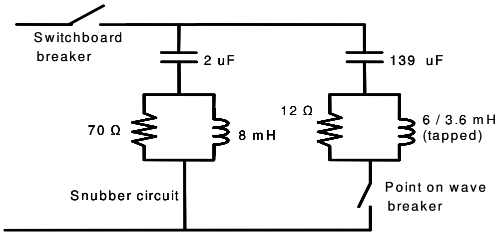


**Fig 4 Per-phase equivalent circuit of a 50 MVAr RPC unit**

The stability of the tripping logic was also analysed for the case of energising the largest JET transformers connected to the 36 kV system; the 4 x 18 MVA units supplying the toroidal field converters which are switched together and equivalent to a single 72 MVA unit. The methodology used followed that discussed in [11]. Assuming least favourable switching conditions and 0.8 per unit residual flux linkage, PSCAD-EMTDC studies showed that the peak instantaneous inrush current would be 13.5 kA, distributed as shown in Fig 5 when three incoming 400/36 kV transformers are in service. For Option B, Fig 5 shows the instantaneous peak current flowing through an individual FCL is 4.5 kA which is 93% of the magnitude trip setting and the maximum di/dt of the FCL current was calculated to be 909 kA/sec which is 24% of the selected trip setting, i.e. the FCLs would not operate. The analysis was repeated for the case of two incoming transformers in service and it was concluded that the selected trip settings were also stable for this event. The same conclusions were reached for Option A.

## VIII. FCL STABILITY DURING JET PULSING

The studies described earlier consider individual events on the JET system but do not assess the stability of the FCLs during the complex loading patterns experienced with JET pulsing. It would be extremely time consuming and expensive to model all the individual converter circuits on each of the outgoing 36 kV circuits, and so a pessimistic approach based on lumping the loads together in the PSCAD-EMTDC model was adopted. The loads on each switchboard were aggregated together and represented by two 6-pulse thyristor rectifiers directly connected to the 36 kV system, i.e. the converter transformers and the 12- and 24-pulse converter arrangements are not represented. This presents a more onerous condition than would apply in practice and allows a margin for uncertainty in the equipment details.

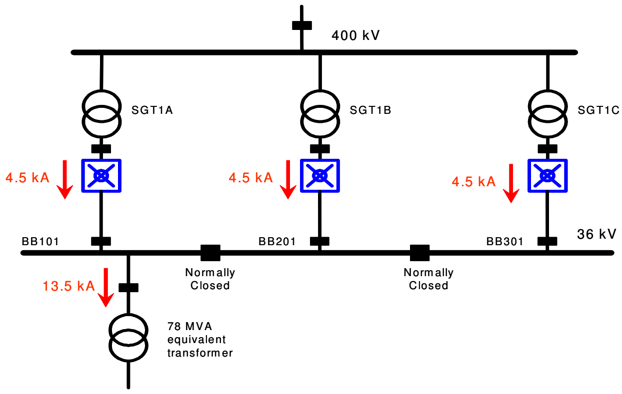


**Fig 5 Distribution of currents when energising toroidal field transformers (Option B)**

The firing angles of the two 6-pulse rectifiers R1 and R2 on each switchboard were derived from the real and reactive power instantaneous demands Pd(t) and Qd(t) as described for the "transient load flow" model. These demands are passed through lag filters as shown in Fig 6. The chosen gains ensure that in the steady state (loaded condition) the loads on each rectifier are different and the use of the lag terms ensures that dP/dt and dQ/dt are different for each rectifier. The signals P1, P2, Q1,and Q2 are used to determine the rectifier firing delay angles α1 and α2 using the approximation pf = cos φ = cos α, and the load resistance on the dc side of each rectifier is continually updated to give the required real power. With this approach one of the rectifiers experiences a rapidly changing firing delay angle which mimics the reactive power swings experienced on the JET system. Extensive simulation studies using the aggregated rectifier load models were performed for both design options to investigate the stability of the proposed

FCL trip settings during a JET pulse. These simulations included transient switching of the RPC units.

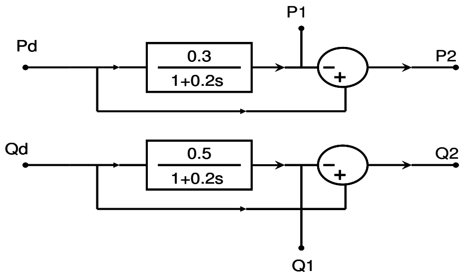


**Fig 6 Algorithm used to calculate P and Q demand for rectifiers**

For both design options A and B the model predicted that the peak instantaneous current flowing through the FCLs was always less than the selected magnitude trip settings, i.e ± 4.86 kA. For design option B, the model predicted that the di/dt trip setting would only be marginally exceeded during one short part of the 90 sec duration of a JET pulse. Investigation of the predicted waveforms revealed that this high di/dt was associated with individual thyristor commutations within one of the six 6-pulse aggregated rectifier load models. The predicted di/dt was considered to be pessimistically high as no allowance for the leakage impedance of the converter transformers is made in the aggregated rectifier load models. It was therefore concluded for design option B that the selected trip settings would not cause incorrect operation of the FCLs during a JET pulse.

For design option A, the instantaneous di/dt calculations performed by the FCL tripping logic were found to exceed the selected trip setting on very many occasions. This is very different from the behaviour observed with option B. Detailed investigation of the predicted time domain waveshapes revealed that there are two distinct but related reasons that account for these differences which could be explained using equivalent circuits.

Firstly, consider a single thyristor commutation on a converter connected to switchboard BB101 as shown in Fig 7. Suppose that the RPC units are not in service and that the commutation creates a di/dt of 4800 kA/sec. The commutation current will divide equally between the incoming transformers which will each experience a di/dt of 1600 kA/sec. The FCL connected between BB101 and BB201 will experience a di/dt of twice this value i.e. 3200 kA/sec. Hence with the FCLs connected between the switchboards, higher commutation di/dts will be experienced compared to the option where the FCLs are connected in series with the incoming transformers.

The second factor to be considered is the impact of the RPC units in sinking the higher order harmonic frequencies associated with the rectifier currents. As already indicated, the RPC units are damped filters nominally tuned to the 5th harmonic with the impedance magnitude and phase characteristics shown in Fig 8. At 50 Hz the filter impedance is 21.6 Ω with a phase angle of -87.9 deg (which corresponds to 50 MVAr at 33 kV). At the tuning frequency the phase changes from capacitive to inductive. As this is a damped filter it presents low impedance above the tuning frequency asymptotically approaching the 12 Ω damping resistance. All higher frequency currents will therefore be attracted to the low impedance of the RPC units.

Consider a single rectifier on BB101, injecting 4 A of current at a harmonic frequency above the 5th as shown in Fig 9. Assuming that no harmonic currents flow into the large (harmonic) impedance of the incoming 400/36 kV transformers, the distribution of the harmonic current between the four RPC units will be as indicated in Fig 9. The harmonic current is distributed equally between the RPC units; 3 A flows through the FCL between BB101 and BB201, and 1 A flows through that connected between BB201 and BB301.

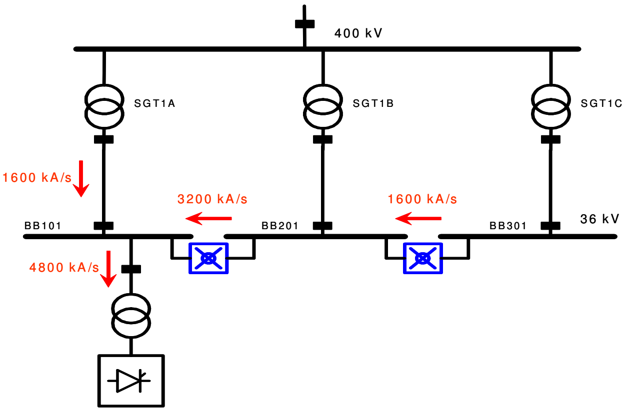


**Fig 7 Distribution of current di/dt for thyristor commutation of converter on BB101 (Option A)**

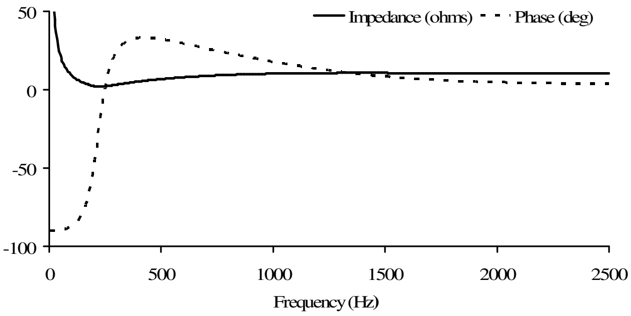


**Fig 8 Impedance characteristics of RPC units (3.6 mH tap)**

With multiple converters on each switchboard all operating at different firing delay angles and different load current levels, the net current flowing through the FLCs will be given by the superposition of a series of current sources connected to each switchboard similar to that shown in Fig 9. It is the significant levels of harmonic currents flowing through the FCLs interconnecting the three 36 kV switchboards which give rise to the high di/dt values predicted by the time domain model.

Although the di/dt trip setting was exceeded for option A, particularly when the RPC units were operational, the model did not predict unwanted operation of the FCLs during the JET pulse as the current magnitude trip settings were never exceeded. Both the magnitude and the di/dt trip settings must be exceeded simultaneously to cause FCL operation.

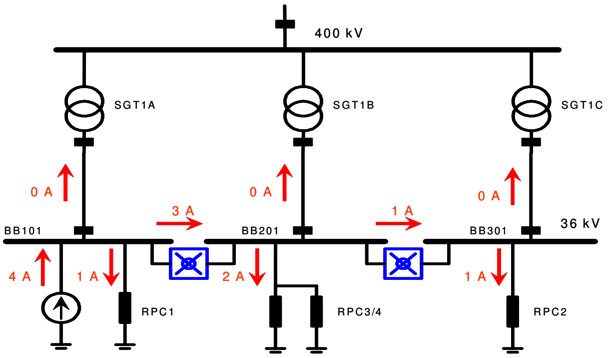


Fig 9 Harmonic current flows with RPC units switched in (Option A)

## IX. DISCUSSION

The transient load flow model has demonstrated the improvement in the voltage regulation that could be achieved by operating all the incoming 400/36 kV grid transformers in parallel. Parallel operation causes the prospective fault currents to exceed the fault ratings of the existing 36 kV equipment and pyrotechnic fault current limiters that rapidly split the system in the event of a fault are proposed to overcome this problem. Two alternative FCL design options are investigated: Option A with two FCLs between the switchboards, and Option B with three FCLs – one in series with each incoming transformer.

The studies show that effective trip settings can be selected for both design options that can discriminate between short circuit currents and RPC unit and toroidal field transformer energisation. Both options satisfy the minimum requirements of reducing the fault currents to levels which are within the ratings of the existing equipment for three-phase and phase-phase faults. Option A has an operational disadvantage in that if BB201 were lost it is not possible to feed BB301 and BB101 in parallel from SGT1A and SGT1C. The advantage of the triangular configuration JET has at present is lost with Option A. Option B provides enhanced performance as it limits the fault contribution of all incoming transformers, i.e. it protects all three incoming transformers from the short circuit current. This enhanced performance requires three FCLs and higher rated units.

Each of the design options offer a viable FCL solution to the problem of increased fault levels when operating the incoming 400/36 kV transformers in parallel. The studies indicate that Option A will be more susceptible to the possibility of a tripping instability associated with the current di/dt signal. This is due to the distribution of the converter thyristor commutation currents and is made worse when the RPC units (damped filters nominally tuned to the $5^{th}$) are switched in due to the harmonic currents that flow between the switchboards.

## X. CONCLUSIONS

This paper has described the unique pulsed power characteristics of the electrical loads at JET; the world's largest experimental magnetic confinement nuclear fusion tokamak. The impetus for the studies described here are the increased pulsed power loads on the JET electrical system, which cause voltage regulation problems on the three 36 kV switchboards.

Extensive time domain simulation studies have been carried out using the PSCAD-EMTDC program to identify a practical method of improving the transient voltage regulation characteristic of the JET 36 kV system. On the basis of these studies it is concluded that the voltage regulation problem on the 36 kV JET switchboards can be significantly reduced by operating the incoming transformers in parallel, and the best approach to mitigate the resulting fault level issues is to use three pyrotechnic fault current limiters – one in series with each incoming 400/36 kV transformer. This approach provides the best engineering solution, with reduced technical risk of incorrect FCL operation.

Further work including measurements of the current transients with the existing 36 kV system configuration are presently underway to provide additional understanding of the unique characteristics of the JET pulsed power load and how FCLs would react to them.

## XI. ACKNOWLEDGEMENT

The studies reported in this paper were completed on behalf of the United Kingdom Atomic Energy Authority (UKAEA), Culham Division. The author thanks UKAEA for permission to disclose the technical information and simulation study results presented in this conference paper. The feedback received from UKAEA staff when preparing this paper is acknowledged.

## XII. REFERENCES

[1] http://www.fusion.org.uk/
[2] J.B. Hicks, M.A. Laughton, "Tokamak poloidal field power supplies", *IEE Proc.-C*, Vol 139, No 2, March 1992, pp 166-174.
[3] C. Damiani, "The JET enhancement programme", 20th IEEE/NPSS Symposium on Fusion Engineering, 14-17 Oct. 2003, pp 636-639.
[4] P. Fransen, "Case History: Electronically Controlled Fault Current Limiters Allow In-plant Switchgear to be Interconnected", *IEEE Trans on Industry Applications*, Vol 33, No 2, March 1997, pp 319-332.
[5] J.C. Das, "Limitations of Fault-Current Limiters for Expansion of Electrical Distribution Systems", *IEEE Trans on Industry Applications*, Vol 33, No 4, July 1997, pp 1073-1082.
[6] A.Y. Hu, Y. Yin, "Fault-Current Limiter Applications in Medium- and High-Voltage Power Distribution Systems", *IEEE Trans on Industry Applications*, Vol 34, No 1, January 1998, pp 236-242.
[7] V. Grafe, K-H Hartung, "Is-Limiter; Reliable and economic protection against short-circuit currents", *Elektrizitatswirtschaft*, 14/1999, pp 720-724.
[8] ABB Calor Emag Mittelspannung GmbH, Ratingen, Germany, Leaflet No DECMS 2249 00 E, 2000.
[9] G&W Electric Co. Blue Island, IL, USA. "CLIP, Current Limiting Protector", Leaflet No SG4-31J, 2005.
[10] M.S Hibbert, K.S. Smith, "Analysis of Unexpected Fault Current Limiter Operation using EMT Programs", Int. Conf. on Power System Transients, Montreal, Canada, June 2005.
[11] K.S. Smith, "Transformer Inrush Studies for Wind farm Grid Connections", Int. Conf. on Power System Transients, Montreal, Canada, June 2005.

## XIII. BIOGRAPHY

**Kenneth Smith** studied at Aberdeen University and joined consultants Mott MacDonald in 2002. He is a Chartered Electrical Engineer with 20 years practical engineering research and development and problem solving experience. He is a member of the IET [formerly the IEE] and the IEEE.