The JET high voltage power distribution, analysis of present and future operational requirements.

N. Dolgetta, E. Bertolini, M. Huart, G. Murphy.
JET Joint Undertaking Abingdon, Oxfordshire, England

Abstract

The JET pulsed loads require power and energy in excess of 1 GW and 10 GJ respectively, supplied by a mixed scheme of energy accumulation and power drawn at 400 kV from the U.K. grid. The direct supply from the grid, in conjunction with the busbars distribution, still provides flexibility and scope for power supplies upgrades. Extensive system studies have been performed and are reviewed consistently with the developments in the operational requirements.

1. INTRODUCTION

JET development calls for continuous modifications and upgrading of the electromagnetic coils and additional heating power supplies. The power distribution uses a mixed scheme of energy accumulation in flywheel generators, and power drawn directly at 400 kV from the U.K. grid. Agreement with the grid Generating Boards allows at present, for power up to 575 MW to be drawn, contractually subjected to technical constraints on the 400 kV line voltage drop and power ramping rate. JET's present plan calls for the upgrade of power supplies to enable operation of the toroidal field coils up to 80 kA for $\simeq$ 10s, from the present 67 kA, and the Neutral Injector power supplies to be partly upgraded to 120 kV DC, with the addition of a new 40 kV booster unit. These requirements and its effects were examined in relation to the supply constraints.

2. THE GRID AND 400/33 kV DISTRIBUTION

2.1 The 400 kV Grid

JET is supplied by a dedicated 400 kV line, connected to the U.K. grid. A review of the JET load impact on the U.K. grid, conducted in cooperation with the Generating Boards in 1986, defined the technical constrains of the supply.

a) Systematic power steps were to be limited to less than 50 MW, while a limited number of higher power steps per year were allowed.

b) Active Power excursion could take place up to 575 MW for periods of less than 60 s every 600 s, and power ramping rate less than 200 MW/s, thus allowing time for the intervention of the generation reserves.

c) Voltage drop on the 400 kV line due to Reactive Power excursion were limited to 1.5%, but relaxed to 2.5% for a period of less than 30 s, to avoid the frequent automatic operation of regulating tap changer transformers in the grid. The short circuit power of the grid S_{cc} varies seasonally, with values over 40 GVA during the winter and a minimum of 15 GVA in summer. Consistently the Reactive Power limit is of 475 MVAR for a S_{cc} of 19 GVA, varying proportionally to the S_{cc} value.

In 1989, experiments aimed to distribute more uniformly the energy radiated from the plasma X-point, resulted in JET drawing power from the grid, oscillating100 MW peak to peak, at 1 Hz, superimposed to the normal power envelope. The Generating Board regarded this as unacceptable, causing excessive electromechanical oscillation in the generators. As the divertor development in JET relied significantly also on the practice of X-point "sweep", the effects on the grid were carefully analysed. The underlying criteria was that the JET operation effects would have to be limited in the same order of the fluctuations which statistically already affect the U.K. grid. The limits subsequently agreed were of 30 MW oscillating power and use of frequency above 2 Hz, as the range of 0.5-2 Hz was too close to resonance frequencies of the grid.

2.2 The JET 400/33 kV Distribution

Three busbars systems are independently fed by 400/33 kV, 300 MVA pulsed rated, Step Down Transformers (SDTs), to limit the 33 kV busbars short circuit power. The transformers are also fitted with tap changers, in 0.3 kV steps, allowing, prior to a pulse, to raise the busbar voltage up to 35 kV. At the same time, the correct functioning of the convertors requires the voltage excursions, during pulses on the 33 kV busbars system, to be contained within 36-29 kV. The thyristor power supplies are supplied through 32 standard breakers, located in the substation building. Although this represents the full capacity of the substation, the standard approach allows reconfiguration of the allocation during shutdown periods, to balance the load requirements on the three busbar systems.

2.3 The JET Loads consist mainly of magnetic field coils and additional heating systems, requiring DC controlled voltage supplies. The toroidal field coils, and the poloidal magnetising coils, are the ones requiring the largest combined power of ≃600 MW and energy ≃9 MJ. For these, a mixed scheme is in place, including thyristor convertors supplied from the grid, and a vertical shaft motor flywheel generator, with diode bridge rectification, in each of the two systems. The plasma radial equilibrium, shape and divertor coils are directly supplied from the grid by independent thyristor convertor, requiring up to ≃220 MW. The additional heating systems, to raise the plasma temperature, are also supplied directly from the grid with a combined power requirement of 200 MW. The divertor coils system, a later addition, and the full power LHCD became operational at JET in 1994. The list of the convertor supplies, characteristics and functions are shown in Table I.

Table I JET Main Power Supplies Datas

MFGC	Motor flywheel generators and diode convertors	2* (85kA, 6.0kV) 2.6 GJ at 225 rpm
TFSU	Toroidal Field Static Units	2* (67kA, 12.6kV)
PVFA	Vertical Field Amplifier	2* (35kA, 2.2kV)
PSFA	Shaping Field Amplifier	1* (35kA, 2.2kV)
PFX	Central Transformer Coils	2* (35kA, 2.2kV)
PDFA	Divertor Field Amplifier	4* (40kA, 0.8kV)
NIB	Neutral Beam Heating	16* (60A, 90kV)
ICRH	IC RF Heating	8* (400A, 28kV)
LHCD	Lower Hybrid current drive	2* (100A, 60kV)

2.4 The Reactive Power Compensation (RPC) system is fully operational at JET since 1994, as the new addition of the divertor coils made RPC even more essential to the routine operation of the JET machine. The RPC system consists of four independent capacitor banks units, connected to the 33 kV busbars via vacuum switches. The switches operation control ('hysteresys' type), is individual to each 33 kV busbar. The closure is triggered once a voltage drop of 1.5 kV is reached and the reopening occurs once the voltage has recovered. Staggered control is used when more than one unit is connected to one 33 kV busbar and the operation of each unit is limited to a single intervention in a pulse. The Reactive Power compensation per unit is equivalent to 50 MVAR at 33 kV.

3. PRESENT POWER REQUIREMENTS

3.1 Present Typical Power Requirements

A pulse representative of the typical demands on the 400 kV grid is #35202, (TF current 62 kA) requiring 350 MW and 270 MVAR. The onset of the four RPC units corresponds, in Fig. 1, to the sharp drops on the Reactive Power trace between times 40 s and 52 s of the pulse. The voltage drop of 1% on the grid indicates that the short circuit power at the time was 27 GVA. On the 33 kV busbars the voltage drops from 34.5 kV to 32 kV.

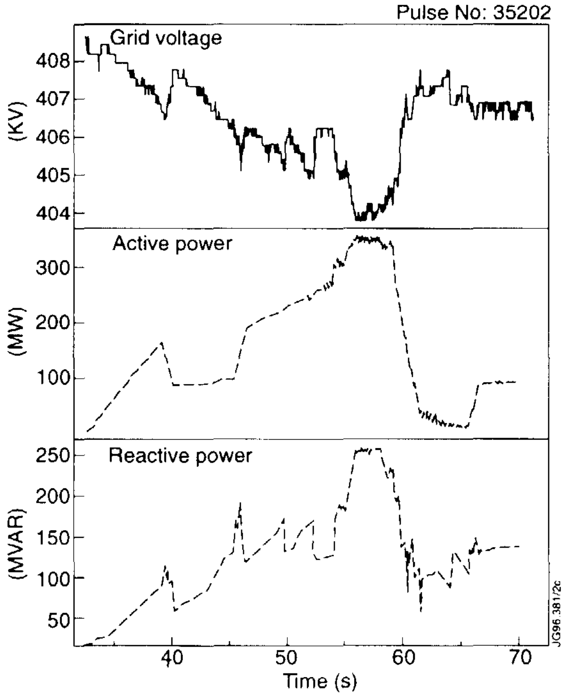

Fig. 1 # 35202 demands on the 400kV grid

For the purpose of the "X-point sweep", the Divertor coils currents, and respective power supplies, are operated in antiphase, with minor net effects on the other poloidal coils. The effects are also filtered by the limited bandwith of the plasma current control loop. Active Power oscillation at 4 Hz result in this case in 20MW peak to peak, mainly due to the PFX power supply, and are generally well within the stated limits.

3.2 Pulse Simulation Codes

Simulations cover the pulse dynamic evolution to account for effects as the sequential control on the TFSUs subunits, staggered intervention of the RPC units, current oscillations in the Divertor coils. A first simulation provides the DC voltages and currents required by the power supply. The code contains the poloidal and toroidal systems models; the toroidal and plasma current are close loop controlled, the error acting on the respective flywheel generator excitation voltage. A second code solves the 'load flow' equations deriving the actual 400 kV line, 33 kV busbars voltages, and the Active, Reactive powers drawn from the grid. These include models of the additional heating, 400/33 kV and RPC system, the AC/DC interface of the thyristor-diode convertors.

3.3 Estimates of Present Maximum Requirements

The results of a 'high power pulse' simulation, are summarised in Table II. The peak power estimates result from the simultaneous operation of different Additional Heating systems which may be required as part of the experimental program. The maximum toroidal field of 3.4 T on the central axis, equivalent to 67 kA, is assumed. The toroidal coils voltage is presently limited to 6 kV. The TFSUs are operated at the maximum combined voltage of 3.5 kV, leaving sufficient margin for control by the generator, but limiting the consumption of its stored energy. Considerable Reactive power is generated by the convertors thyristors control firing angle, and also by the TFSUs convertors, operating at full voltage, due to the thyristors overlap commutation angle. The TFSU transformer leakage inductance is, on the other hand, required to limit the short circuit current. The Divertor coils power supply generate significant Reactive Power as the voltage rating is mainly required in reversed mode, to maintain control at no current, and for-modulating the current at few Hz during the 'X-point sweep'. The 400/33 kV Step Down Transformers (SDTs) are the other major source of Reactive power.

The oscillating power due to the practice of the "X-point sweep" at 4 Hz remains well within the limit of 30MW peak to peak.

Table II JET Power Supplies Requirements

Scc GVA Vstart 406 kV Vbb start 34.5 kV

Bus1	TSFU1	PFX	NIB	RF
I DC kA	67	25	6*.06	3*.15
V DC kV	2*.75	2*.08	92	20
P MW	110	26	33	9
Q MVAR	52	58	26	13
Bus2	TFSU2	PVFA	NIB	RF
I DC kA	67	15	6*.06	3*.15
V DC kV	2*.75	2*.05	92	20
P MW	110	15	33	9
Q MVAR	52	52	26	13

Bus3	D1	D2	D3	D4	NIB	RF	LH	PSFA	AUX
I DC kA	15	35	35	15	4*.6	6*.15	.33	40	-
V DC kV	.1	.2	.2	.2	92	20	60	.9	-
P MW	2	9	10	2	22	18	20	40	7
Q MVAR	16	26	28	12	18	26	9	35	27

	Loads P MW	Loads Q MVAR	SDT Q MVAR	RPC Q MVAR	V kV
Bus 1	180	152	42	-42	30.3
Bus 2	170	145	37	-43	30.5
Bus 3	130	197	31	-85	30.6

	Total P MW	Total Q MVAR	V kV	ΔV %
JET	480	430	396	2.4

4. ASSESSMENT OF FUTURE UPGRADES

4.1 The TF 4T Upgrade

The operation at 4T (78 kA), 9 s. flat top, is foreseen to take place within the present TF coil temperature limits, which translate in a allowable I^2t of 11 x $10^{10}A^2$ s. The voltage limit on the TF coil set at 8 kV, allows to achieve this result, containing the I^2t 'exhausted' in the current ramp up phase. Maximum voltage and power requirements are related to the current rise phase, especially near to the current flat top value. The operation of the TF system requires the TF flywheel generator, to retain, after the 'current rise phase', enough energy, or rotational speed, to effectively control, in closed loop the TF current. To operate at 4T with 9 s. flat top, the TFSUs are to provide a combined voltage of 4.5 kV at 78 kA, and require to be upgraded, replacing their present transformers. The TFSU thyristor bridges are already capable of 78kA and will require fewer modifications, while the flywheel generator and diode convertor are already suitable for 80kA. The upgraded TFSUs will each be capable to supply 2.25kV at 78kA compared to the present 1.5kA at 67kA. The transformers leakage inductance is to increase proportionally to the transformer rating to limit the short-circuit current at the present level. The Active Power drawn by the TFSUs is expected to raise from the present 220 MW to 350 MW, and the associated Reactive Power to increase from the present 105 MVAR to 175 MVAR. The increased current through the 400/33 kV SDTs would also raise the Reactive Power, due to the SDTs leakage inductance, from ≃110 to ≃185 MVAR. The latter scaling quadratic with the transformers currents.

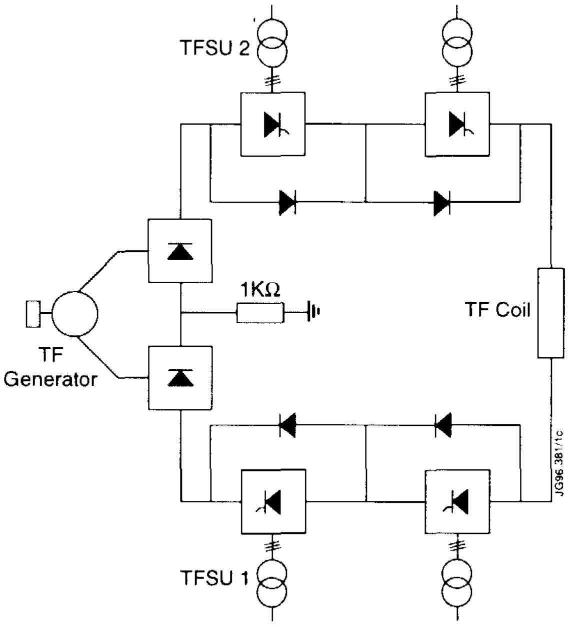

Fig. 2 Toroidal field system

The effects on the 400 kV grid and 33 kV busbar system were assessed, considering the number of available RPC units unchanged. The loads requirements, other than the TFSUs, as outlined in Table II, were maintained, apart for the omitted LHCD. The results show that, in these conditions, JET demands for the Active and Reactive would reach 590 MW and 560 MVAR respectively. The voltage drop on 400 kV grid results limited within 2.5% for grid short-circuit power S_{cc}>23 GVA, which is the case for most of the year outside the summer period. The power rating of the 400/33 kV SDTs (300 MVA), on the two busbars supplying the TFSUs, would be reached but not be exceeded. The voltage on the 33 kV busbars, considering large combined additional heating would drop to a minimum of 29.5 kV. The loads distribution appears fairly balanced, but this depends on the actual usage. With the flexibility to swap loads between busbars optimisation is still under evaluation.

Table III JET High Power Scenarios at 4T

Scc 23 GVA Vstart 406 kV Vbb start 34.5 kV					
	Loads P	Loads Q	SDT Q	RPC Q	V
	MW	MVAR	MVAR	MVAR	kV
Bus 1	240	130	80	-40	29.5
Bus 2	240	130	80	-40	29.5
Bus 3	110	115	25	-85	30.5
	Total P	Total Q	V	ΔV	
JET	MW	MVAR	kV	%	
	590	560	396	2.5	

The effects on the grid due to the routine operation at 67 kA (3.4T), with the upgraded TFSUs transformers were also investigated to verify the compliance of the 2.5% voltage drop limit, down to the S_{CC} 19 GVA level, as at present. In these conditions , the combination of one full TFSU unit and another TFSU subunit only, would be supplying power. Simulations showed that for 67 kA operation the upgraded TFSUs would not draw any larger Reactive power than at present and the limitations would be the same.

5. CONCLUSIONS

The study performed in relation to the 4T Toroidal Field upgrade, shows that this will be compatible with the present JET power distribution system and the contractual supply constraints. The power distribution design has proven to be a major asset for the project, allowing, over the years, the additions and developments required by the experimental programme.

REFERENCES

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