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## ABSTRACT.

This paper presents a design for a new power supply, named Enhanced Radial Field Amplifier (ERFA), for the vertical stabilization of the plasma column in the JET machine. The aim is to increase the performance compared with the Fast Radial Field Amplifier (FRFA, in operation at JET since the early 1990s) and to control the plasma in the new demanding scenarios that will be produced in JET after the EP2 enhancement phase. After discussing the performance required of ERFA, the paper describes the specific solution identified and illustrates the main criteria followed for the design of the system, highlighting the peculiar choices and the motivations behind them.

## 1. INTRODUCTION

The feedback stabilization of the plasma column vertical position plays a fundamental role in the operation of the JET machine. Vertical Displacement Events (VDEs), which can be triggered in operating scenarios with Edge Localised Modes (ELMs) [1], are produced and need to be properly controlled to avoid plasma disruptions. A radial magnetic field, created by external coils, performs the control of the vertical position of the plasma against VDEs. Presently, the Fast Radial Field Amplifier (FRFA) [2] supplies the coils; this amplifier is composed of four units each rated 2.5kV, 2.5kA which can be configured to deliver either 10kV, 2.5kA or 5 kV, 5kA. The first configuration is preferred, as it provides a faster response thanks to the higher voltage available. The power supply is based on Gate Turn-Off thyristors (GTOs) and is controlled in open loop by the Vertical Stabilisation (VS) controller, which is part of the Plasma Position and Current Control (PPCC) system of JET [3].

After the EP2 enhancement project [4], that will increase the additional heating power (either up to 35MW for 20s or 17.5MW for 40s) and will provide JET with an ITER-like wall, it will be possible to study plasma regimes relevant for ITER, such as ELMy H-mode scenarios. In these scenarios, large ELMs are expected that produce an excursion of radial field in excess of the present FRFA current and voltage stabilization capability, triggering a VDE that could lead to plasma disruption. As a consequence, the JET operational space is limited for achieving plasmas with high triangularity and high plasma energy at high current. The importance of JET operation in this domain in view of ITER suggests an enhancement of the VS system and in particular of the radial field amplifier capability.

Initially, the procurement of a new power amplifier was compared against the option of upgrading the existing FRFA. The latter was eventually abandoned and a new radial field amplifier, named Enhanced Radial Field Amplifier (ERFA) was considered to replace FRFA.

The conceptual design described in the following represents only one of the possible solutions for ERFA; the performance enhancement may be achieved with different approaches, based on other schemes and technologies.

## 2. PERFORMANCE OF THE ERFA

VDEs are characterized by different growth rates. The chance of success of the vertical stabilization action depends on the rapidity of the amplifier in producing the required current in the radial field coils; in fact, at constant growth rates, the faster the current variation in the coils, the lower the value of the current needed to stabilize the plasma. On the other hand, given a certain value of the current derivative on the coil, higher growth rates of the instability require higher current rating of the amplifier to be handled. These considerations suggest that an enhancement of the vertical stabilisation capability must be aimed at increasing both the radial field amplifier current and the current derivative produced in the coils. The latter can be obtained either by raising the average voltage of the amplifier or by changing the radial field coil configuration.

In FRFA, the average output voltage (at the input to the output filter) can assume up to nine discrete values, from –10 kV to +10 kV with steps of 2.5kV, while the current is ±2.5kA. This amplifier works in open loop to optimize the dynamic performance and receives an analogue reference signal from PPCC representing the required voltage; the voltage is delta controlled with hysteresis.

ERFA will be an upgrade doubling the current capability to ±5kA and raising the output voltage, taking into account that the highest value acceptable by the coils insulation is 12kV. An additional goal is the minimization of the overall response time of the amplifier in order to reduce the time interval between a PPCC request and the application of the voltage to the load. As for the load, the coil inductance is about 20 mH; a further enhancement of the system performance can derive from a reduction in the number of turns in the coils. This option is currently under investigation; so the design of ERFA must foresee the possibility to work with a reduced load inductance.

Actually, the request to ERFA in terms of current, voltage and switching frequency depends on the evolution of the plasma vertical instabilities during the pulse. Since this evolution is unpredictable, ERFA must be able to apply a voltage to the load and to switch this voltage between different levels at any “reasonable” frequency, restricted only by the intrinsic limits of the amplifier. Even if a predictable operating condition cannot be recognized, some reference standard diagrams, which clearly state the maximum duties in terms of frequency, current and voltage, were worked out. Two examples are reported in figures 1 and 2. The waveforms of fig. 1 show a condition in which ERFA is requested to switch between the maximum positive and negative voltages. The current swings from –500A to +500A in the first 59s, and from –5000A to +5000A for the following 1s. This diagram reproduces operation of ERFA in absence of instabilities, followed by a final instability requiring the full swing for 1s. The frequency of the oscillations is determined by the load inductance (20 mH in the figure); depending on the coils configuration and on the plasma behaviour, this parameter can change in the range of 5-25 mH and the frequency of the oscillations changes accordingly.

Figure 2 represents a situation in which repeated VDEs, requiring the full current swing, are taking place. Here, during a 60s pattern, 250ms with ERFA supplying a base current of 500A alternate with 10ms current bursts at 5 kA; a ripple is superimposed on these base currents, given by the ±3kV voltage oscillation at 2500 Hz during the 250ms interval, and by a full voltage swing at 1000 Hz during the 10 ms interval. In this case, the load inductance value affects the ripple current but not the frequencies, which are predetermined.

## 3. CONCEPTUAL DESIGN OF THE ERFA

### *3.1 GENERAL STRUCTURE*

The performances required to ERFA can be fulfilled with different technical solutions. Here, one possible scheme is studied, based on the availability of a recent power component named the Integrated Gate Commutated Thyristor (IGCT); the same component is used in a power supply of comparable ratings which is in operation at Consorzio RFX since 2004 [5], feeding the toroidal winding of the experiment.

The number of ERFA units is directly related to the number of voltage steps required on the output. As in FRFA, four units are connected in series at the output, as shown in fig. 3. Each unit is rated for higher voltage and current: 3kV, 5kA to obtain the total required performance (12kV upstream of the output filter, 5kA). The number of steps available is therefore nine, of 3kV each, from –12kV to +12kV. Due to the fast dynamics required on the load, the basic unit structure with an output H-bridge inverter fed by a capacitor bank and an input ac/dc conversion system is maintained.

### *3.2 THE AC/DC CONVERTER AND THE DC LINK*

The scheme of the dc link section was worked out assuming that the capacitor bank handles the high power peaks in transient conditions leaving the ac/dc converter the duty of compensating the losses. During the ramp-up phase of the load current, lasting for some ms, the energy is transferred from the capacitance to the coil inductance via the inverter at the expense of the dc link voltage; on the other hand, in the case of load current ramp-down, the energy stored in the coils is fed back to the dc link, thus causing a corresponding voltage increase. As a result, when ERFA performs the specification diagrams, the maximum output voltage available from each unit fluctuates between a maximum and a minimum value.

A typical approach to the dc link design consists in controlling the voltage with a fixed reference corresponding to the nominal voltage required and in selecting the capacitor bank size so that the voltage excursion stays within the maximum and minimum allowable values.

An alternative option was adopted for the ERFA design, based on the following considerations. In normal conditions, without instabilities, the system operates at low current; the current ramps-up as soon as the instability compensation is required, causing a reduction of the capacitor bank voltage. Therefore, it is convenient to set the dc-link voltage as high as possible at low currents, in order to guarantee the maximum voltage as soon as the compensation begins; conversely, at high currents, it is convenient to set the dc-link voltage to a reduced value, thus increasing the capacitor bank capability to absorb the energy in case of recovery from the load. This strategy, in which the ac/dc converter voltage reference depends on the output current, allows a reduction in the size of the capacitor bank as the equivalent admissible voltage excursion is doubled with respect to that obtained with the previous design approach. Moreover, if the required current excursion is lower, the average voltage applied to the load is higher.

Excessive energy coming from the load that would result in a dc-link overvoltage can be managed either by returning the energy to the JET distribution system via four-quadrant ac/dc converters, as in FRFA, or dissipating it with a system of choppers and resistances. The latter approach is selected for ERFA as it allows faster dynamics and simplification and increased reliability of the ac/dc converter – transformer system. Although this solution implies energy dissipation, in practice the chopper intervention would not be frequent, being not foreseen in normal operating conditions.

Figure 4 shows a sketch of the main voltage and current waveforms of the ERFA unit in case of a high power transient. The waveforms are calculated assuming a coil inductance of 20mH, a capacitor bank of 50mF, a chopper resistance of 1.2W with two intervention thresholds set at 3.1 and 3kV. The voltage reference for the thyristor converter is calculated on the basis of the load current, varying linearly from 2750V at 5kA to 3000V at no load. The dc chopper, which is hysteretic controlled between two thresholds, guarantees that in any case the voltage can not go over 3.1kV.

### *3.3 THE INVERTERS*

The design of the inverters strongly depends on the type of semiconductor chosen for the application. Here, a commercial IGCT was selected and its ratings were considered for the analyses, both in normal operation and fault conditions. A single-phase H-bridge arrangement was chosen for the inverter; with the selected IGCT, a simple structure with one IGCT component per switch and two basic bridges connected in parallel is possible. The thermal analyses, carried out considering the conduction and the switching losses, confirmed that the selected topology is sufficient to avoid over-temperatures in the components. The analyses were performed under the assumptions that an optimization technique is used to control the inverter units that allows reducing the equivalent commutation frequency and therefore the losses. Further details on this technique are given later on.

Finally, the minimum turn-on and turn-off times of the selected IGCT, which are of the order of some tens of microseconds, allow an improvement to the response time of the ERFA to a voltage request as these times are much smaller than those of the GTOs in the FRFA inverters.

### *3.4 THE OUTPUT FILTER*

The maximum tolerable voltage derivative applied to the radial field coils by the ERFA is 800V/ms. To meet this requirement, some form of smoothing of the inverter output voltage is needed. A solution based on passive components was adopted in the proposed design for the ERFA. The structure of the filter and the choice of the parameters were performed paying particular attention to minimizing the power losses and the voltage drop, which directly affects the voltage available to the load. Efforts were made to reduce as much as possible the series inductance of the filter, compatible with the voltage derivative limitation requirement and with the need to limit the over-current in case of short circuit or misfiring of the bipolar crowbar.

### *3.5 CROWBARS*

Crowbars for protection purposes are provided both on the dc-link and at the output, downstream of the filter, based on thyristors. The dc-link crowbar acts as a fast discharge device for the energy stored in the capacitor bank in case of severe fault to the ERFA unit. It is equipped with a Break Over Diode to assure the passive intervention also in case of fault in the control system.

The output crowbar is bipolar and is composed of two fully redundant thyristor branches and of a mechanical switch connected in parallel. In case of plasma disruption, the output crowbar is fired. The mechanical switch is designed to take the full I2t fed back from the load. Moreover, if an ERFA unit trips, this crowbar is used to bypass the unit, possibly for up to the full pulse duration (60s). In this way the system is able to carry on at reduced performance but still guaranteeing a stabilisation capability.

### *3.6 CONTROL AND PROTECTIONS OVERVIEW*

In the proposed ERFA control scheme, open loop operation is maintained and modulation of the H-bridge inverter at fixed frequency is avoided in order to guarantee the required dynamics. The reference is sent to the amplifier by the PPCC system in a digital format, for example an integer identifying the required voltage level within the nine available values. The reference is processed by the ERFA control; a control algorithm decides which unit must be turned on and which turned off. The dispatching algorithm was optimised in order to reduce the equivalent switching frequency of the single semiconductor and, therefore, its switching losses; the optimisation strategy was worked out observing that the extreme values of the output voltage (+12 kV and –12 kV) are obtained only with one combination of the switches (all inverters on), whereas the intermediate levels can be delivered in more than one way, depending on which of the inverters is on: consecutive switching at the same voltage can involve different semiconductors, thus reducing the switching frequency of the single component down to _ of the output voltage frequency.

Since the frequency of the commutation is not under direct control of the power supply, protection functions are foreseen to avoid damage to the units due to excessive switching frequency demand. As in FRFA [6], the temperature of the semiconductors must be simulated in real-time and sent back to PPCC; in this way PPCC can decrease the request as appropriate to avoid tripping the unit. A limitation on the peak current is also foreseen which commands the zero voltage state of the inverters if the maximum current is reached with PPCC asking for more current. Concerning the protection management logic, it is of fundamental importance not to shut down all ERFA units in case of a trip in a single unit, with complete loss of the stabilisation action and, as a consequence, a plasma disruption. The structure of the protection logic must be studied in order to allow the completion of the pulse with a reduced number of units, whenever possible.

## 4. SYSTEM SIMULATIONS

The ERFA scheme has been simulated with PSIM program [7] in order to verify that the conceptual design is able to meet the specifications. The simulations were also a useful tool to assess the electrical stresses on the different components in terms of currents, voltages and I2t and to test the proposed concept concerning the control of the dc-link voltage.

Diagrams of fig. 1 and 2 were simulated at different specified loads, taking into account the variations of the JET distribution voltage. As an example, the main waveforms obtained when the system is generating the outputs of fig. 2 are reported in fig. 5. It can be noted that the largest excursions of the dc link voltage are obtained when the load current ramps up and down. The minimum dc link voltage is 2500V, as required, while the peak value is 3070V, below the upper chopper intervention threshold. The ac/dc converter output current is limited to 400A thanks to the current limitation loop implemented in the control.

## CONCLUSIONS

A new amplifier was studied to replace the FRFA of JET with enhanced vertical stabilisation capabilities. The enhancement has been obtained by increasing the current, the average voltage and by reducing the overall response time with respect to the FRFA. The proposed structure of the ERFA consists of four units connected in series at the output, but the design of the system was based on a different concept, which combines an appropriate control of the dc link voltage by means of the ac/dc converter with the presence of a chopper with discharge resistors connected in parallel to the capacitor bank. As a result, the specified performances have been obtained with a reduced capacitor bank size and reduced converter power and complexity compared with FRFA. The results of the system simulations proved the adequacy of the circuit topology and the suitability of the design.

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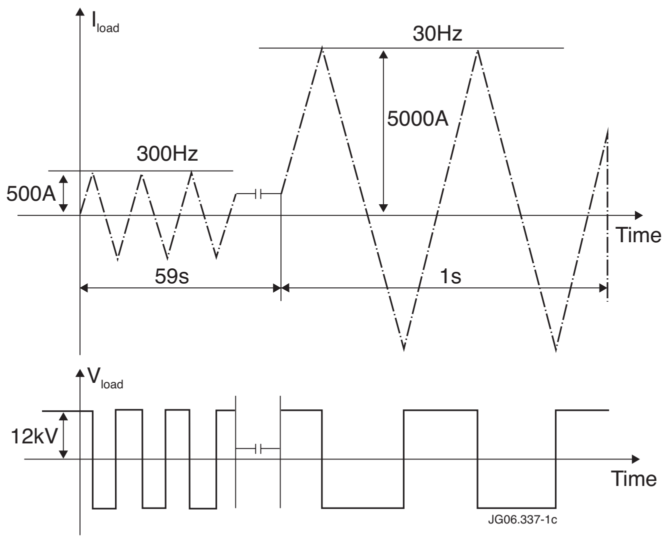


*Figure 1: First set of output reference waveforms (upper: current, lower: voltage) for ERFA specifications. Reference load inductance is 20mH.*

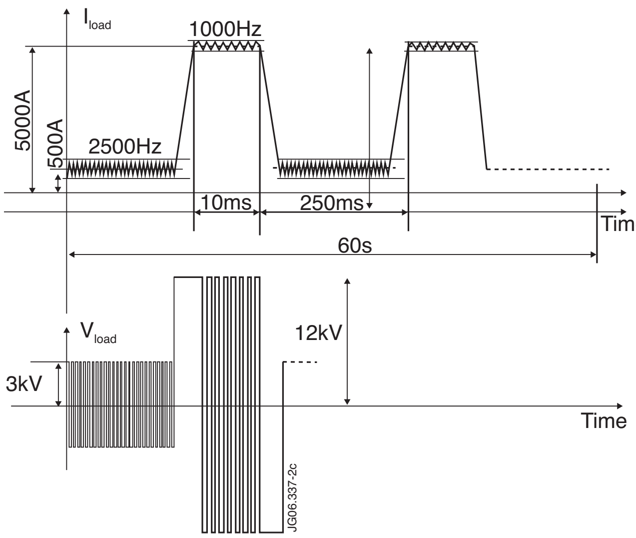


*Figure 2: Second set of output reference waveforms (upper: current, lower: voltage) for ERFA specifications.*

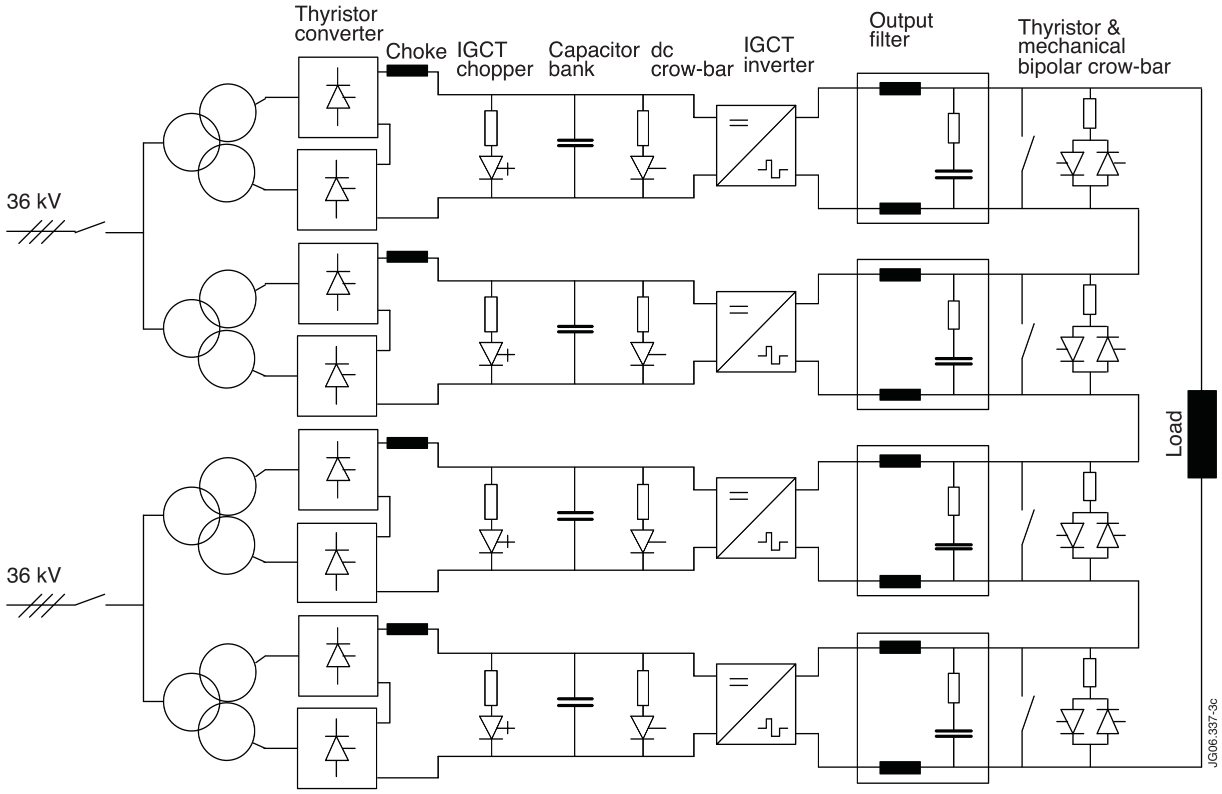
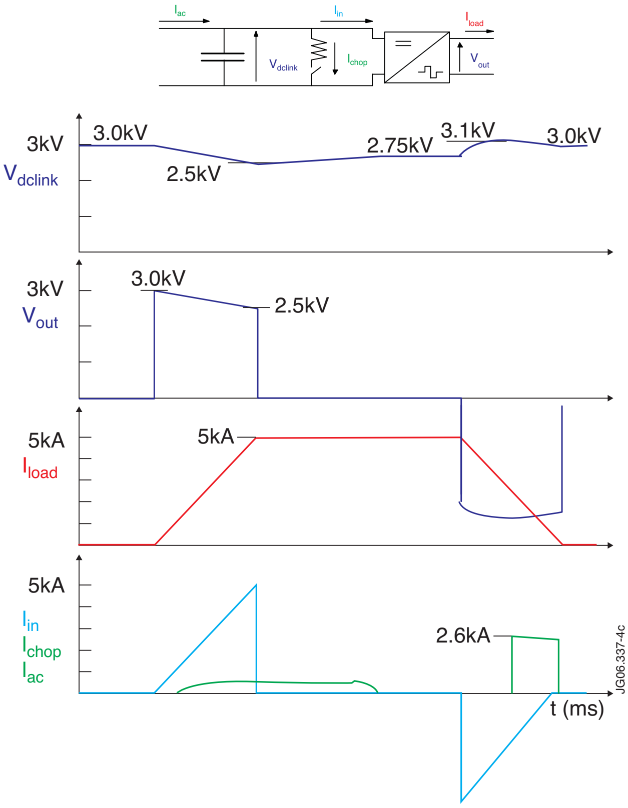


*Figure 3: Scheme of the proposed ERFA system.*



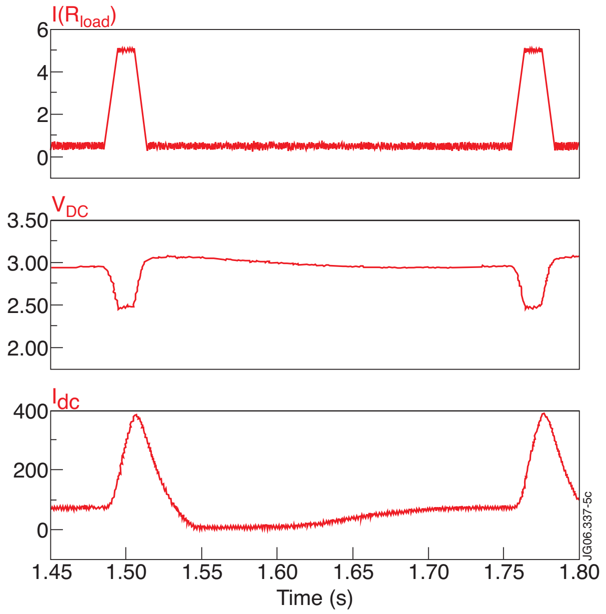


*Figure 4: Main voltage (upstream of the filter) and current waveforms of the ERFA unit in case of a high power transient.*

*Figure 5: ERFA output current (upper plot), dc link voltage (central plot) and ac/dc converter output current (lower plot) simulating the diagram of figure 2.*