Circuit Analyses of the Filament Ion Source Power Supplies for the ITER Neutral Beam Test Facility

M. Bigi, L. Zanotto

Consorzio RFX, Euratom-ENEA Association, Corso Stati Uniti 4, 35127 Padova, Italy
DIEE, Università degli Studi di Cagliari, Piazza d’Armi 09123 Cagliari, Italy

Abstract—This paper describes circuit simulations of the filament heating circuit for the neutral beam test facility of the International Thermonuclear Experimental Reactor (ITER). The novel features of ITER filament heating circuit are studied both in normal operation and under fault conditions. The proposed scheme is found capable of performing as required and results are illustrated useful for further detailing of the design.

I. INTRODUCTION

In fusion devices the principle of neutral particle injection involves an ion source, from which an ion beam is extracted, subsequently accelerated electrostatically to the required energy and finally neutralised for focusing into the plasma. For the International Thermonuclear Experimental Reactor (ITER) Deuterium neutral beams of 1MeV energy and up to 50MW total power are foreseen [1]. In the present design of ITER NB injector [2], Deuterium negative ions are produced in a high current arc source, where the arc is sustained by thermionic electrons emitted by hot filaments. Two distinct power supplies are involved, a high current low voltage power supply driving the arc and high current circuits for filament heating.

To address the scientific and technological challenges posed by the ITER neutral beam system, construction of a Neutral Beam Test Facility (NBTF) is expected to be launched in the near future. In the framework of the European studies on the NBTF, this paper describes circuit simulations for the design of the arc ion source power supplies. The layout of the ITER filament heating circuit adopts novel solutions [2] as illustrated below, and the primary objective of the analyses is to investigate basic operation of the proposed scheme. Then the fault conditions of the filament heating circuit are simulated, studying whether reliable fault detection may be provided by transducers at locations convenient for access, more distant from the injector. The circuit model also gives indications on the requirements for filtering of the arc current.

II. THE ITER FILAMENT HEATING CIRCUIT

The arc ion source of ITER reference design [2] has a total of seventy-two tungsten filaments, heated by line frequency alternating current of 200A 15V rms per filament (Table 1). The filaments are arranged in twelve identical groups of six filaments each. The filament heating circuit is three-phase and the filaments are configured as a delta load, with three pairs of parallel connected filaments in each group. To minimise the length of high current cabling for filament heating, each filament group is supplied through a three-phase step down transformer installed close to the ion source. On ITER the nearest available location is distant about 10m from the injector, outside the biological shield.

The supply to the filaments, along with the other electrical, cooling and gas supplies to the injector, is carried by a High Voltage dc transmission line, that on ITER will operate in a difficult environment [1]. To reduce conductor count in the congested transmission line, the cabling for filament heating is also exploited to carry the return of the arc current, connecting the filament transformer to the negative terminal of the arc power supply. This is a common solution, found e.g. on the Joint European Torus [3], where filament heating is performed by monophase ac. On JET, the centre taps of the secondary windings of the filament transformer are connected to the negative terminal of the arc power supply. This design ensures that the fractions of the arc current flowing in the two winding halves are balanced, with no net dc magneto-motive force (m.m.f.) to disturb ac operation of the transformer. A similar concept is reflected in the ITER scheme, where the mid points of the filament transformer secondary windings are connected to the negative terminal of the arc power supply. However the insertion of diodes (D1/D2/D3 in fig. 1) is necessary, because the three centre taps are at different potentials. On the other
hand, the three-phase solution offers a major advantage by halving the number of conductors required in the transmission line.

Three-phase supply to the filaments and, as a consequence, use of diodes in the connection between filament circuit and arc power supply are unprecedented. The simulations described here are intended firstly to investigate basic operation of the ITER NB filament circuit. Secondly, fault scenarios are studied, with a view at determining whether plant protection may be afforded by instrumentation located outside the reactor biological shield, i.e. in circuit terms, by transducers installed on the primary side of the filament transformer.

In a neutral beam injector, the extracted beam current is closely related to the arc current [4]. The arc ion sources of neutral beam injectors are operated in a mode known as “emission limited”, where arc current depends on the available thermionic electrons [5]. In this regime, varying filament heating will vary arc current and in turn beam current [4]. Similarly to existing injectors, the filament circuit for ITER NB also includes an ac regulator (the thyristors shown in fig. 1) of the voltage supplied to each filament transformer, as means to control filament heating. The heavily distorted waveforms output by the regulator [6] are included in the circuit model.

<table>
<thead>
<tr>
<th>TABLE 1: SPECIFICATIONS OF THE ITER FILAMENT CIRCUIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of filaments</td>
</tr>
<tr>
<td>Filament rms current and voltage</td>
</tr>
<tr>
<td>Filament transformer</td>
</tr>
<tr>
<td>Arc voltage</td>
</tr>
<tr>
<td>Arc current</td>
</tr>
</tbody>
</table>

III. THE CIRCUIT MODEL OF THE ARC

In the ion source filled by a gas at low pressure [7,8,9], a difference of electric potential is established by the arc power supply between the chamber and the filaments. Under this voltage, the thermionic electrons emitted by the hot filaments drive an arc [5].

Items of the ITER filament circuit like cables and transformers have a known model with lumped circuit elements. On the contrary, modelling of filaments and arc is not straightforward. More generally, arc phenomena are complex and understood only to an extent [10].

Resistance of the tungsten filament is time varying and non linear, due to temperature dependence. However once the filaments have reached their operating temperature, typically around 2800K [11], and a stable beam extraction has been established, temperature variations become smaller and linear resistance may be attributed to the filaments.

The arc current is associated with thermionic emission, which is a distributed phenomenon. Here the simplest lumped approximation is adopted, injecting the arc current into the centre points of the filament resistors. The choice of the direct current injecting elements needs to guarantee that:

a) the voltage-current characteristic of the arc, at constant filament heating, exhibits positive resistance [4,7,12];
b) at constant arc voltage and in thermal equilibrium, an increase of filament heating causes an increase in arc current.
c) a minimum voltage is needed to sustain the arc;
d) minimum filament heating is needed to maintain the arc.

In our simulations the model of the arc shown in fig. 2 was used, composed of the series of a thyristor with the parallel of a current source and a linear resistor. The thyristor voltage drop is representative of the arc voltage, nominally 100V for ITER [2]. The pulse to the thyristor gate is present only when the rms value of the filament current is greater than a threshold. The rms value of the filament current also controls the current source. This circuit model, satisfying all the requirements outlined above, was replicated for each of the six filaments of a group.

Among other features, the resulting circuit model ensures that when a filament fails in open circuit the corresponding fraction of the arc current is also lost, coherently with experimental observations [13].

IV. ANALYSIS OF NORMAL OPERATION

Basic operation of the filament heating circuit for one group of six filaments was simulated in PSIM [14], with the arc model described above. At this stage, a linear model for the three-phase filament transformer was in use, disregarding core saturation effects. The thyristor ac regulator was also excluded and the supply waveforms considered sinusoidal. It was found that the diodes connecting filament transformer to negative terminal of the arc power supply (hereinafter diodes D1/D2/D3, refer to fig. 1) switch like in a half-wave rectifier. In fact the cathodes of the diodes are at the same potential, whereas the anode potentials constitute to all effects a three-phase system of voltages. Except for the overlap during commutations, in a period of the supply voltage each diode is in conduction for 120 electrical degrees.

The switching dynamics of the diodes casts doubt on the operation of the filament transformer. With only one diode in conduction at any given time, net dc magnetomotive forces are present in the secondary windings, potentially leading to saturation of the transformer core.

[Diagram: Fig. 2: circuit model of the arc current. The tilted square with an arrow inside symbolises a current controlled current source.]
Following these results, the transformer model was upgraded to feature non linearity of the magnetic core. The transformer also had to have winding centre taps accessible for connection to external circuits. To meet these requirements, a transformer element was developed in PSIM specifically for the present study, based on a three leg magnetic circuit coupled to the winding electrical network. A non linear m.m.f.-flux characteristic with saturation, taken from the data of a real transformer, was implemented and the working point, in absence of arc current, placed at the knee of the curve. The resulting transformer model was validated with ac supply before being included in the filament model.

With the upgraded filament model, initially run for sinusoidal supply and in absence of arc current, the effects of transformer non linearity on the primary side line currents are observed as small 5th harmonic deformation, about 4% of the fundamental.

In presence of the rated arc current, the simulations show that diode switching does not cause core saturation, because of the limited amplitude of the resulting dc m.m.f. The increase in the peak value of the secondary m.m.f. is 17%. From the primary side line currents, the arc current is evident in the increase of rms value (+17%) and in the appearance of even harmonics, mostly 2nd harmonic. The essence of these observations stays true even when the ac regulator is included. The delay in firing the thyristors heavily deforms the waveforms (Fig. 3) and on the primary side 5th and 7th harmonics of the line currents grow of importance. Even harmonics however remain the characteristic signature of the arc current. The figures quoted refer to a thyristor firing delay angle of 26°, corresponding to filament rated current (200A rms) when the primary voltage is at the rated value (420V rms) and under the assumption of transformer impedance of 5%.

V. ANALYSIS OF FAULT SCENARIOS

Fault conditions of the filament circuit identified in the light of the operating experience of existing injectors were considered and found relevant to the ITER scheme:

a) filament failure in open circuit;
b) filament failure with short circuit to arc anode.

Moreover the following fault condition, peculiar to the ITER design, was identified:
c) failure in short circuit of one of diodes D1/D2/D3.

Fault c), effectively short circuiting part of the secondary windings, determines significant overcurrent in the ac supply and is easily diagnosed. The corresponding protective action is tripping or disabling of the affected filament group. Fault b), potentially drawing a large current from the arc power supply, is dangerous for the integrity of the ion source and halts operation of the whole injector. Fault a) is comparatively frequent and also more difficult to detect in a three phase system with heavily distorted waveforms (Fig. 4). In these conditions the combination of harmonic and symmetrical component analysis [15] may be employed. To determine whether fault detection can be performed from measurements taken on the transformer primary side, attention focuses on the primary line currents. The simulations show that the fault of a single filament causes a first harmonic inverse sequence component of some significance (almost 10% as large as the direct sequence component), a circumstance on which design of on-line protection circuits may be based.

As operation with few failed filaments represents a normal circumstance for neutral beam injectors, the ITER circuit simulations must address the effect of filament failures on the remaining filaments of the same group.

The worst case scenario with two filament failures in the same phase, causing complete loss of that phase, was studied. For a thyristor delay angle of 26°, one of the remaining phases experience an increase (+7%) whereas the other a decrease (-8%) of the rms value of the filament current.

![Fig. 3](image1.png)  
*Fig. 3: simulation of filament circuit operation. Comparison between primary side line current with (black) and without arc (red), for a thyristor delay angle of 26° and for rated arc current of 8kA (670A per filament group).*

![Fig. 4](image2.png)  
*Fig. 4: simulation of filament fault. Comparison between the three-phase system of primary line currents in absence of filaments faults (black) and with one filament failure (red). The phases are identified by the sequence of the positive maxima starting from t=0, c a b. The faulty filament is between lines a and b of the delta connected filament load.*
VI. ARC CURRENT RIPPLE

As a consequence of finite resistance of the arc characteristic and of diode switching, the simulated arc current shows third harmonic ripple (fig. 5). This variation in time is also accompanied by non uniformity in space, due to the different potential of the three phases with respect to the arc chamber. To reduce the arc current ripple, the insertion of passive components in the dc path was studied. Two possibilities were considered, a ballast resistor like on JET [16], specified for a voltage drop at rated current about 50% as high as the arc voltage, and a smoothing inductor of 200µH (per filament group). In the simulations the smoothing inductor performs better (fig. 5). However in these analyses the arc power supply was modelled in a crude manner, simply as a dc voltage source.

Conclusions

The simulations of the ITER NB filament circuit revealed the switching behaviour of the diodes connecting filament transformer to the negative terminal of the arc power supply. Given a standard transformer design, the resulting unipolar m.m.f does not cause core saturation. However the anticipated direct components of the secondary currents linked to this special duty will have to be considered when specifying the filament transformer.

The fault simulations indicate that filament failures can be detected from measurements taken on the transformer primary side, guiding lay out of the instrumentation required for this part of the ITER neutral beam test bed.

Finally, inductance in the arc current dc path appears the most promising method of filtering the ripple of the arc current caused by diode switching and ac regulation.

ACKNOWLEDGMENT

This work would have not been possible without the support of the JET and MAST neutral beam and power supply teams at Culham. Their help on design and operating experience of neutral beam systems was extremely valuable. The authors also wish to acknowledge the many fruitful discussions with fellow members of the power supply group at the RFX experiment in Padua.

This work, supported by the European Communities under the contract of Association between EURATOM/ENEA, was carried out within the framework the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

[8] G. Delogu et al., The drift source: a negative ion source module for dc multi-amperes ion beams, Rev. Sci. Inst. 70 12 (99)
[12] F. Bottiglioni et al., Large area ion source for neutral beam injection, 12th Symposium On Fusion Technology, Jülich 1982
[14] www.powersimtech.com

Fig. 5: comparison of arc current ripple in different scenarios, without additional passive elements (black), with 50V ballast resistor (green) and with 200µH smoothing inductor (red). The main ripple is third harmonic, however a sixth harmonic component is also present due to ac regulation by the thyristors.