Contributed Paper

Wave Form of Current Quench during Disruptions in Tokamaks

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Abstract

The time dependence of the current decay during the current quench phase of disruptions, which can significantly influence the electro-magnetic force on the in-vessel components due to the induced eddy currents, is investigated using data obtained in JT-60U experiments in order to derive a relevant physics guideline for the predictive simulations of disruptions in ITER. It is shown that an exponential decay can fit the time dependence of current quench for discharges with large quench rate (fast current quench). On the other hand, for discharges with smaller quench rate (slow current quench), a linear decay can fit the time dependence of current quench better than exponential.

Keywords:
Tokamak, disruption, current quench, ITER

1. Introduction

Several aspects of disruptions in ITER can have major impact on the design of the machine. Of particular importance among them are the large thermal loads on the divertor during the thermal quench, which can influence the lifetime of the divertor target plates, and electro-magnetic (EM) force on the in-vessel components, such as blanket and divertor modules, and vacuum vessel due to eddy and halo currents induced during current quench phase. These aspects have to be taken into account properly in the design, particularly in the supporting structure of the blanket modules. Regarding the life time issue, recent large progress of mitigation techniques such as impurity gas injection [1], prediction of major disruptions using neural network method [2] will substantially reduce the number of events where full thermal energy is deposited on the target plate. Thus, the life time issue can be expected to be significantly relaxed relative to the presently assumed design basis (disruption frequency \(\approx 30\%\)). Nevertheless, small numbers of disruptions or vertical displacement events (VDE) will have to be accommodated in order to maintain a wider flexibility of plasma operation in ITER as an experimental reactor. Therefore, the machine must be designed to withstand EM forces due to disruptions even without mitigation. This design assumption is particularly relevant for the major disruption case, where not all of the disruption can be detected and mitigated before the event. VDEs are caused by the failure of the vertical control system and

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are thus expected to be rare. In addition, mitigation techniques will be applied during the plasma displacement (= 0.5 s) before the current quench starts. However, even in this case, a VDE without mitigation would occur at least once or twice during the full life of the machine. Based on these considerations, the present ITER has been carefully designed to withstand the EM force induced by the major disruptions and VDEs [3]. In order to confirm the robustness of the design, it is of primary importance to evaluate the EM force for the representative disruption scenarios using a sophisticated numerical code based on the relevant physics.

The current quench rate and the time dependence of the current quench, that is the ‘wave form’, are essential for the estimation of EM forces on the in-vessel components during the current quench phase. For the current quench rate, comprehensive databases have been created in the ITER Physics Basis [4]. However, the database on the wave form of the current quench has not been created yet. Furthermore, physics guidelines have not yet been established on which kind of wave form should be combined with the specified quench rate in the database. In this paper, we will examine JT-60U data archived in the ITER database and make an initial attempt to derive a guideline for the current quench wave form.

2. Current Quench Rate and Wave Form

One of the most essential physics assumptions for the evaluation of the EM force due to the induced eddy current is the current quench rate after the thermal quench. The experimental database for the quench rate is summarised in the ITER Physics Basis [4]. In the database, data for $\tau/S$ are archived from major tokamak machines (ASDEX-U, Tore-Supra, JET, JT-60U, TFTR, DIII-D). Here, $\tau$ is the current quench time and $S$ is the plasma poloidal cross section before the quench. Noting that $L/R$ time of the plasma column scales approximately with $S$, $\tau/S$ can be interpreted as the current quench time normalised by $L/R$ time. In most of the divertor tokamaks, plasmas are highly elongated and therefore usually move in the vertical direction during the disruption, which leads to a reduction of the plasma cross section. Therefore, the initial cross section area should be interpreted as an approximate measure for representing longer $L/R$ time for larger plasmas. In Ref. [4], it is indicated that $\tau/S$ values scatter significantly depending on the discharge conditions, while a lower boundary exists for each machine. Here we will use the lowest value observed in JT-60U, which corresponds to 1.3 ms/m² as a conservative guideline. When multiplied by the ITER cross section area $S = 21$ m², $\tau = 27$ ms is obtained. This corresponds to a current quench rate $dI_p/dt \approx 560$ MA/s.

Another important physics assumption, which influences the EM force considerably, is the current quench wave form. Since the minimum $\tau/S$ of 1.3 ms/m² has been derived from the maximum (instantaneous) quench rate in Ref. [4], the EM force will be somewhat overestimated in some blanket module or could be underestimated in other modules, if a simple linear wave form of the current quench with $dI_p/dt \approx 560$ MA/s is used. In order to show the effect of the current quench wave form, predictive disruption simulations both for linear and exponential wave forms are performed by a sophisticated plasma equilibrium evolution code DINA [5]. The DINA code has been developed to simulate a dynamic evolution of 2D plasma equilibrium on closed and open magnetic surfaces together with external circuit (PF coils and surrounding conducting structures). Flux surface averaged transport equations are also solved simultaneously. Extensive effort has been made to validate the code in many tokamaks [6-8], and, thus, it is one of the most suitable and sophisticated codes for the present purpose. It differs from another sophisticated code, TSC [9], in that free boundary Grad-Shafranov equation is solved instead of solving the equation of motion, so that the plasma equilibrium under evolving conditions (either vertically stable or unstable) is obtained at each time step.

Figure 1 shows the modelled PF coils and the
vacuum vessel and the initial starting plasma equilibrium. PF coils are passive, i.e., short circuited in the present calculation and vacuum vessel is modelled by small sized passive toroidal conductors. Blanket modules are not connected toroidally, so that they are not included in the calculation of equilibrium. Actually, however, eddy current induced in the blanket modules can somewhat affect the plasma behaviour, especially in the fast time scale of an order of 1 ms, e.g., plasma movement due to fast beta drop and fast change of internal inductance during the thermal quench phase. Accurate calculation of the effect of blanket modules needs three dimensional model for the plasma behaviour and thus is beyond the scope of the present analysis. An approximate modelling of this effect by equivalent toroidal conductors with appropriate short $L/R$ time is in progress and will be reported elsewhere in the future.

Here one representative scenario is examined i.e., center disruption, in which the thermal quench first occurs when the plasma sits at a specified position of the current center. After the thermal quench, the plasma current quench starts. At the same time, vertical stability is lost and the plasma starts to move upward due to unbalanced eddy currents on the vessel.

Initial plasma parameters before the thermal quench are those of the nominal values for the inductive reference operation scenario of ITER, which are summarised in Table 1. Figures 2 and 3 show the simulation results of the time evolutions of the plasma current (Fig. 2-(a) and Fig. 3-(a)) and equilibrium (Fig. 2-(b) and Fig. 3-(b)) for the case of linear current quench wave form ($I_p/(dI_p/dt) = 27$ ms), and of exponential wave form (time constant $\approx 27$ ms), respectively. Here, we will use the following analytical formulas to evaluate the EM force (or moment) on a typical blanket module. Eddy current $j$ induced on the blanket module due to the change of flux $\Phi$ is calculated from the circuit equation

$$\frac{dj}{dt} + j/t_c = -1/L \cdot d\Phi/dt \quad (1)$$

where $t_c = L/R$, $\Phi = B_n A$, $B_n$ = magnetic field normal to the plane of the circuit (assumed to be uniform on the blanket module), $A = cross-section area of the current loop. The inductance $L$ and resistance $R$ of the current loop are given by $L = K \mu_0 A/l$ and $R = \rho p/l d$, where $K$ = shaping factor, $l$ = thickness of the circuit, $\rho$ = resistivity, $p$ = perimeter of loop, and $\mu_0$ is permeability. $d$ is the penetration depth of the magnetic field into the blanket within $L/R$ time. The resistivity of the SS316L(N) used in the analysis is 1.4 $\mu\Omega$ m considering the cavity of the cooling channels. The induced current in the circuit $I$ can be analytically solved as

$$j = \exp(-t/t_c) \left[ l/(K\mu_0) \right] \int -dB_n/dt \cdot \exp(t/t_c) \cdot dt \quad (2)$$

Table 1 Major plasma parameters at the initial state just before the thermal quench for disruption simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma current $I_p$ (MA)</td>
<td>15</td>
</tr>
<tr>
<td>Internal inductance $\ell_i$</td>
<td>0.85</td>
</tr>
<tr>
<td>Poloidal beta $\beta_p$</td>
<td>0.7</td>
</tr>
<tr>
<td>Position of current center (R, Z) (m)</td>
<td>(6.2, 0.5)</td>
</tr>
</tbody>
</table>
produce radial and poloidal torques, Mr(ΔBr) and Mp(ΔBp), through the interaction with the toroidal field. The toroidal eddy current induced by the change of radial field ΔBr produces the toroidal torque Mt(ΔBr), through the interaction with the poloidal field. Schematics of these eddy currents and the resultant torque are summarised in Fig. 5. The toroidal eddy current is also induced by the poloidal field change ΔBp, which produces the toroidal torque of Mt(ΔBr) through the interaction with the radial field. The torque Mt(ΔBr) is relatively small compared to the torque Mr(ΔBp) and, thus, is omitted in the figure.

Figures 6 and 7 show calculation results of Mr and Mp for each module at several time moments both for linear and exponential current quench wave forms given in Figs 2 and 3, respectively. EM forces resulting from Mr and Mp are supported by different supporting structure (key structure for Mr and flexible joint for Mp), so that they must be assessed separately. Proper assessment of the maximum moment for each module is essential for the design of each blanket module. Except Mr for one particular module, Nr. 2, the maximum (absolute) values of both moments Mr and Mp for the linear wave form are larger than the exponential wave form by (15–25)% This difference of the maximum moment is actually significant, since the EM force is close to the design limit and as much margin as possible is desirable to ensure robustness of the design.

Based on these results, proper specification of the current quench wave form is important to conduct a robust design for each blanket module against EM force arising from disruptions. So far, the current quench wave form has not been clearly specified in the database. In order to obtain the guideline for the wave form, we have examined the wave form observed in various disruptive discharges of JT-60U experiments. Through this examination, it is found that the majority of the current quench wave forms can be fitted either by exponential-like or linear-like wave forms. Fig. 8 shows a typical example, in which exponential–like wave form can fit the experimental wave form much better than linear. The data corresponds to one of the experimental data with the smallest τ/S of 1.3 ms/m² ((dIp/dt)max ≈ 560 MA/s). Here closed circles show the experimental value, solid curve with open squares shows the best fitted exponential curve, and dashed line shows the simple linear wave form with (dIp/dt)max ≈ 560 MA/s. It is clearly seen that the exponential curve is a much better fit than the simple linear curve with (dIp/dt)max. The degree of fitness is indicated by RMSE, which is defined later.

In some discharges, however, a linear-like wave form can fit the data better than the exponential-like wave form. Such an example is shown in Fig. 9. Apparently, experimental values (solid circles) are much better fitted by linear-like wave forms (solid line with open squares) compared with the exponential-like wave forms (dashed curve), which can also be easily judged by their respective RMSE. It should be noted that, in this discharge, the current quench is much slower than that of Fig. 8 (τ/S is 2.84 ms/m² in Fig. 9). In this case, (dIp/dt)max is almost identical to the time derivative of the linear fitting line.

In order to investigate the wave form more
systematically, we will introduce the fitness parameter, RMSE (root mean square error), which is defined as

$$\text{RMSE} = \sqrt{\frac{\sum_{i} \sigma_{\text{fit},i}^2}{N}}$$

(3)

$$\sigma_{\text{fit},i} = \left(1 - \frac{I_{\text{fit},i}}{I_{\text{exp},i}}\right)$$

(4)

Here, $I_{\text{fit}}, I_{\text{exp}}$ and $N$ are the plasma current by fitting function and by experiments at the $i$-th data point and total number of data points, respectively. In this study, both exponential and linear fitting functions are examined as representative fitting functions. Note that smaller the RMSE values correspond to improved fitting. Many disruption shots in JT-60U with a variety of current quench rates were selected from the ITER disruption database [4] for this study (the selection was not necessarily systematic). We have restricted the fitting analyses to a certain range of plasma current, i.e., from $I_{p0}$ to $(0.2–0.3)I_{p0}$, where $I_{p0}$ is the plasma current just before the thermal quench. This is because, in the later phase of the current quench, the current quench rate tends to be reduced significantly due probably to runaway or suprathermal electrons, especially for many of the fast current quench discharges. This feature can be seen in Fig. 8, in which current quench rate becomes
significantly reduced when the plasma current is below 1 MA. First, let us compare RMSE for the linear fitting with \((dI_p/dt)_{\text{max}}\) and the exponential fittings with \(\tau = I_p_0/(dI_p/dt)_{\text{max}}\).

Figure 10 shows RMSE for each fitting as a function of \(\tau / S\) (closed circles for linear and open squares for exponential fitting). It is seen from this figure that the exponential fitting is much better than the linear fitting for fast current quench discharges when \(\tau = I_p_0/(dI_p/dt)_{\text{max}}\) is simply used for fitting, while, for slower quench discharges, linear wave form can fit the current quench equally well as the exponential wave form. Note that these fittings are not necessarily the best fitting to reproduce the current quench wave form, since \(\tau = I_p_0/(dI_p/dt)_{\text{max}}\) is used instead of \(\tau\) minimising RMSE. Therefore, the next step is a comparison of the fittings providing minimum values of the RMSE for both fitting functions. The results of this comparison are
shown in Fig. 11. Note that RMSE obtained in Fig. 11 are much smaller than those of Fig. 10, especially for the linear fitting wave form, since the best \( \tau \) is used for the fitting. From Fig. 11, some clear features for the current quench wave form can be drawn as follows.

1. When \( \tau/S \) is relatively small, the current quench is described by exponential wave form.
2. When disruption is characterised by a relatively high value of \( \tau/S \), the linear fitting is better than the exponential fitting.

3. Conclusions and Discussions

Both the current quench rate and the wave form during plasma disruption influence the EM force on the in-vessel component due to the induced eddy current. It is shown that the exponential wave form can fit the current quench for fast current quench discharges (small \( \tau/S \)). On the other hand, for slower current quench discharges, the linear wave form can fit the quench better than the exponential. These conclusions are derived from data analyses mainly for major disruptions in JT-60U. Further data from other tokamaks are needed to confirm the conclusions derived in this paper. In addition, data analyses for VDEs should probably be performed separately, since the wave form for VDEs may be somewhat different from those of major disruptions. This requires additional experimental effort to obtain a systematic set of data by intentionally triggering VDEs, since, like JT-60U, VDE events are usually very rare in the present tokamaks.

One possible physical reason for these different wave forms is the existence of runaway or suprathermal electrons. For vertically elongated plasmas, the plasma usually tends to move vertically after the thermal quench due to up-down asymmetry of the induced eddy currents in the structure. The plasma cross section will be reduced due to this movement. Hence, if the plasma temperature after the thermal quench is not appreciably changed during the current quench phase, which is observed in DIII-D [10], the current quench wave form tends to be deviated from an exponential wave form with \( L/R \) time constant, and the resultant wave form becomes linear-like. When the current quench is very fast, however, runaway or suprathermal electrons, which are driven by the induced high loop voltage, will play a significant role to prolong the current quench due to their longer \( L/R \) time [11]. This process will deviate the wave form from linear-like to exponential-like. Further examinations are necessary to confirm this speculation.

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