International Journal of Energy Research

INTERNATIONAL JOURNAL OF ENERGY RESEARCH
Int. J. Energy Res. 2016; **40**:497–506
Published online 13 December 2015 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/er.3455

Theoretical investigation of plasma dynamical behavior and halo current analysis

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SUMMARY

In this paper, a novel system has been developed for plasma disruption conditions followed by downward vertical displacement. During the disruption, size and orientation of plasma decreases, which gives the halo current circulated around each contacting point in radial as well as in poloidal directions. Therefore, a new mathematical model has been developed, which gives the interaction forces of halo current, vertical, and radial plasma dynamical behavior (linear and nonlinear). This theoretical approach showed that the tokamak plasma has two connecting points in order to distinguish between the stable and unstable position. This model can particularly give the magnetic field change points and changing of flux, which are more convenient in order to discuss the static and tilting position of plasma behavior. Numerical techniques have been calculated in terms of plasma dynamical behavior, that is, Electromagnetic/plasma, Vertical Displacement Event (VDE) stages, and initial interaction between the forces under specific time interval. The objective of the research is to developed theoretical and computational model in order to investigate the dynamical behavior of plasma under disruption conditions. This is the novel method, and no work has been reported so far. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS

theoretical calculations; vertical displacement event; dynamical behavior; halo current analysis; plasma VDO model

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Received 13 August 2015; Revised 5 October 2015; Accepted 12 October 2015

1. INTRODUCTION

The most advanced tokamak reactor in the world is named as experimental advanced superconducting tokamak (EAST) [1,2]. This tokamak has the capability of attaining steady state operation under high confinement mode [3,4]. In 2012, the reactor achieved longer pulse generation in 411 s in 32S H-mode at 0.28 MA plasma current [5]. During the operational state of EAST, there is a need to analyze the plasma behavior (initial-to-final state) to maintain the plasma in the same orbit for the long pulse generation. The coupling technique includes electromagnetic force, interaction forces of halo current, and force on the vessel including vertical and radial and plasma control models (linear and nonlinear) [6,7]. A new system needs to be designed in order to point out the plasma behavior with dynamical system [8]. This system discusses the steady state condition and sensitive dependent on initial condition based on same isolated points and conjugated parameters. This is the most important step for further research, and all system solutions depend on these points and parameters. Different well known numerical techniques have already calculated the plasma behavior of tokamak with collision term, which is perfectly able to examine the plasma behavior in magnetic field change points.

In this paper, theoretical model has been developed that denotes the behavior of perturbation with iterative time step, that is, as $\Delta t = 0.01$ and $\Delta t = 0.001$ in the range of $t \in [0.02–0.14]$ and allows calculating the behavior of particle distribution function. In addition, it has been observed that the vertical displacement of plasma in downward direction is slower than the upward movements. Therefore, plasma behavior description from static to tilting moments needs to be calculated as well.

No theoretical explanation has been published so far, only few work has been reported in the literature, which are only linked with experimental details, that is,

- M. Okamoto *et al.* gives the interaction between plasma disruption and wall in HYBTOK-II tokamak by using triple probe. They observed that wave form of plasma quench has two phases, that is, slow and then fast decay process that influence the rapid movement of plasma to the inner wall as well [9].
- J. Li *et al*. find out the effect of plasma disruption on magnetic system in EAST tokamak and calculates the temperature effect experimentally [10].
- M. Zhang *et al.* calculates the protection assessment of magnetic system during disruption of tokamak and developed an overvoltage model [11].
- Axially Symmetric Divertor Experiment (ASDEX) upgraded team at Italy including R. Aledda *et al.* analyzing the length of disruption phases using Upgraded ASDEX (AUG) prediction system. The modification has also been compared with locked mode detector as well [12].
- H. R. Strauss calculates the relation of tororidal current asymmetry and vertical current moment; they analyze the behavior of toroidal variation of the toroidal plasma current and 3D (three dimensional) halo current [13].
- S. P. Gerhardt describes the dynamics of disruption halo current toroidal axisymmetries. They observed that the halo current have strongly asymmetric structure when enter the lower divertor [14].

The current research deals with theoretical modeling of plasma interactions, vertical displacement event (VDE), interaction forces, and halo current. The research has been carried out under following dimensions.

- Plasma behavior for stability analysis in 3D views.
- Exactly calculate the magnetic field change points during VDE.

Following objectives lie under the research

- To develop plasma dynamical model that can control and easily analyze plasma VDE
- To develop model used to analyze the interaction forces for halo current.

2. RESEARCH METHODOLOGY

The research is focused on the plasma dynamical behavior based on the coupled analysis of electromagnetic force, interaction forces of halo current, force on the vessel (vertical & radial), and plasma control models (linear and nonlinear). In these criteria, different mathematical approach has been chosen, and new computational model for calculating different aspects of tokamak reactor is developed. The analyses of plasma control oriented linear model, plasma close loop model, and plasma regression model for the control of plasma current have been coupled altogether internally. The proposed plasma model performance proved in a current drive profile trajectory tracking problem used a modified anti-windup proportional-integral-derivative-based control scheme. In the same way, a simple linear model based on loop control voltage have been derived depends on plasma linear model. Lorentz transformation and stretch-twist-fold system have been merged by using interlink techniques, and these systems were considered to be nonlinear system. Lorentz transformations can also be used to prove that magnetic and electric fields are simply different aspects of the same force, that is, the electromagnetic force as a consequence of relative motion between electric charges and observers. The Lorentz transformation has been used to provide the electromagnetic field quantities upon changing the frame of references. For this reason, the magnetic field is required to compel the fluid to be in the same orbit. We have used the modification of toroidal and poloidal coordinates system and equilibrium model for short control tokamak plasma in linear and nonlinear models and then developed nonlinear plasma dynamical system for tokamak. This system gives two same isolated points and free parameters theta 1 and 2 that can provide the analysis of plasma total vertical/radial force, interaction forces of halo current, and dynamical behavior of particular orbital motion with system (A) matrix. Computational techniques have been used to investigate the dynamical behavior of plasma under disruption conditions, VDE stages, and initial interaction between the forces under specific time interval. The entire research methodology is presented as theoretical model in Figure 1. The system of equations and models that are used for tokamak machine are included in Table I.

3. THEORETICAL INVESTIGATION OF PLASMA DYNAMICAL BEHAVIOR

In order to calculate and evaluate new innovative model to examine different aspect of tokamak, mathematical approach has been developed. In this model, specific parameters used to analyze the steady state condition and sensitive dependent on initial condition have been calculated. This work exactly calculates the magnetic field change points during VDE and analysis of halo current. The generated poloidal field internally produced altogether due to toroidal currents in primary winding. For critical analysis of all aspects of this research, nonlinear plasma behaviors of dynamical system have been developed and are given as

$$\dot{x}(t), \dot{y}(t), \dot{z}(t) = \begin{cases} Cz - x^2 z^2 a \cos\theta \\ x^2 y - Cz^2 + \beta + \delta + 5, \\ x2 - \beta\delta x + Cz^2 \cos\theta \end{cases} \tag{A}$$

where

$$x = R_0 + a_p \cos(\theta + \delta \sin\theta)$$
$$z = Z_0 + k a_p \sin\theta$$
$$y = y$$

In this system (A), if $C \neq 0$, then the plasma may composed of two same connected points $(0, \pm 0.2, \pm 0.2)$, and

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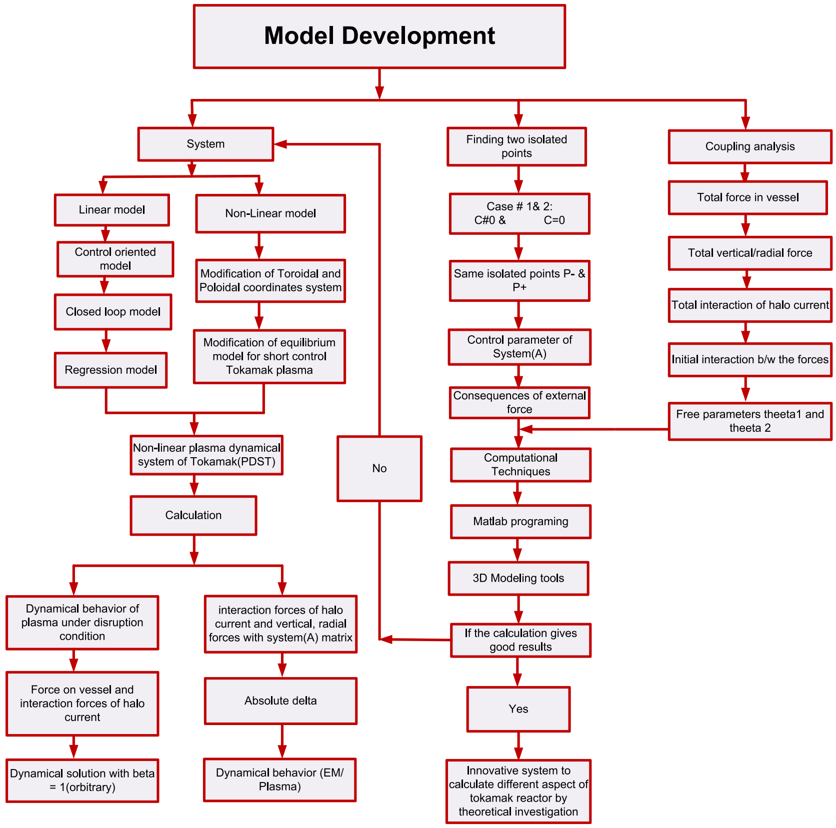

Figure 1. Flow diagram of research methodology.

Table I. Governing equations and models of tokamak machine.

$I\,{}^{d}L/_{d}t + L^{d}I/_{d}t + RI + nv_{arc} = -{}^{d}\varphi/_{d}t$	•Current induced by the magnetic flux change during position instability
$\frac{d}{dt}\left[(M+R).\begin{pmatrix} h \\ \varphi \end{pmatrix}\right] + K.\begin{pmatrix} h \\ \varphi \end{pmatrix} = \frac{d}{dt}\left[(M+R).\begin{pmatrix} h_0 \\ \varphi_0 \end{pmatrix} + \varphi_0\right]$	•Eddy current by Lagrangian formulation
$\begin{bmatrix} M & 0 \\ 0 & 0 \end{bmatrix}\begin{Bmatrix} \ddot{u} \\ \ddot{T} \end{Bmatrix} + \begin{bmatrix} 0 & 0 \\ -C_e & U \end{bmatrix}\begin{Bmatrix} \ddot{u} \\ \ddot{T} \end{Bmatrix} + \begin{bmatrix} K & C_s \\ 0 & R \end{bmatrix}\begin{Bmatrix} u \\ T \end{Bmatrix} = \begin{Bmatrix} F^{ex} \\ B^{ex} \end{Bmatrix}$	•Eddy current and structural coupled system
$1/\mu_0 \nabla^2 A = \sigma\left({}^{\partial}A/_{\partial}t + \nabla\varphi - v\times B\right) - J_P$	•Governing equation of electromagnetic field
${}^{1}/_{\sigma}\nabla^2 T - \mu_0\left({}^{\partial}T/_{\partial}t + {}^{1}/_{4}n\int{}^{\partial}T/_{\partial}t\nabla^{1}/_{R}dS\right) = {}^{\partial}B_0/_{\partial}t,$	•Governing equation of current vector potential method
$nm\left({}^{\partial}v/_{\partial}t + v\cdot\nabla v\right) = -\nabla\cdot P + nF + R$	•Equation of motion
${}^{3}/_{2}n^{d}T_j/_{d}t = -p_j\nabla\cdot v_j - \nabla\cdot q_j - \prod_{j\alpha\beta}{}^{\partial}v_{j\alpha}/_{\partial}x_\beta + Q_j$	•Energy balance equation

if $C=0$, the plasma behavior pointed out the quadratic curve as

$$-x^2\alpha\cos\theta = 0 \tag{1}$$

$$x^2y + \beta + \delta + k + 5 = 0 \tag{2}$$

$$kx^2 - \beta\delta x = 0 \tag{3}$$

By Eqs. (1) and (3), plasma has the quadratic curve, that is,

$$x^2\left(\beta^2\delta y + 1\right) + \beta^2 x + x^2 + 5\delta\beta^2 = 0 \tag{4}$$

If$C\neq 0$, plasma has two same isolated points, that is,

$$p^-: (0, -0.02, -0.02) \text{ and } p^+: (0, +0.02, +0.02).$$

The isolated points of system (A) comprises of one-saddle focus-nodes, which shows that this system (A) is perfectly suitable to find out the dynamical solution.

Because the objective of the research is to find out the plasma dynamical behavior of VDE Up/Down. Therefore, if $e > 0$, the system (A) can be able to control negative plasma real value, and if $e < 0$, system (A) can be able to control positive plasma real value. Hence, any external force (sin (θ)) is unable to disturb the system in y-direction as

$$yx^2 + Cz^2 + \beta + \delta + 5 + \sin(\theta) = 0 \tag{5}$$

However, parameter 'e' can be controlled as an outcome of x, z-direction and limits the behavior of the system under two conditions. First, if the parameter of the system (A) has fixed value as

$$\{\alpha = C > \delta > \beta\} \in [0.1, 80] \tag{6}$$

then, the system (A) can be effected by external force only in x, z-direction. Therefore, control parameters are able to adjust these values. Secondly, if the system (A) has arbitrary values, that is,

$$\sum_{i=0.1}^{8} C_i\alpha_i, \sum_{j=8}^{20} \delta_j, \sum_{l=1}^{90} \beta_l \tag{7}$$

then, it is able to control the system affected by external force in x, z-direction.

dependent on initial condition as depicted in Figure 2 as shown later.

3.1. From plasma system (A)

θ_1 and θ_2 are free parameters and have been located by the conditions, that is, if $t > 0$ or $t < 0$, which is the same parameters as connected points p^+, p^- using transformation $t = -1/T(\ln(\tau)), t = +1/T(\ln(\tau)), \alpha = C = 0.1$, β is arbitrary, and τ is in milliseconds.

$$\begin{aligned} -T_1\tau\dot{x}(\tau) &= Cz - x^2\alpha\cos\theta \\ -T_2\tau\dot{y}(\tau) &= x^2y - Cz^2 + \beta + \delta + 5 \\ -T_3\tau\dot{z}(\tau) &= x^2 - \beta\delta x + Cz^2\cos\theta \end{aligned} \tag{8}$$

Let

$$\left\{ \begin{array}{lcl} x(\tau) = +\sqrt{C(\alpha\beta)} + \sum_{n=1}^{\infty} a_n\tau^n & & x(\tau) = -\sqrt{C(\alpha\beta)} + \sum_{n=1}^{\infty} d_n\tau^n \\ y(\tau) = +\sqrt{C(\alpha\beta)} + \sum_{n=1}^{\infty} b_n\tau^n & , & y(\tau) = -\sqrt{C(\alpha\beta)} + \sum_{n=1}^{\infty} e_n\tau^n \\ z(\tau) = +\sqrt{\beta^2\delta^2 - \beta^2\delta^2} + \sum_{n=1}^{\infty} c_n\tau^n & & z(\tau) = -\sqrt{\beta^2\delta^2 - \beta^2\delta^2} + \sum_{n=1}^{\infty} f_n\tau^n \end{array} \right\} \tag{9}$$

Substituting Eq. (8) in Eq. (9),

$$\begin{aligned} -T_1\tau a_1 - 2T_1\tau^2a_2 - 3T_1\tau^3a_3 - \cdots &= \left(C\sqrt{\beta^2\delta^2 - \beta^2\delta^2} - \alpha a_1^2\cos\theta\right)\tau + \left(C\sqrt{\beta^2\delta^2 - \beta^2\delta^2} - \alpha a_2^2\cos\theta\right)\tau^2 + \left(C\sqrt{\beta^2\delta^2 - \beta^2\delta^2} - \alpha a_3^2\cos\theta\right)\tau^3 + \cdots \\ -T_1\tau b_1 - 2T_1\tau^2b_2 - 3T_1\tau^3b_3 - \cdots &= \left(a_1^2b_1 - C\left(\beta^2\delta^2 - \beta^2\delta^2\right) + \beta + \delta + 5\right)\tau + \left(a_2^2b_2 - C\left(\beta^2\delta^2 - \beta^2\delta^2\right) + \beta + \delta + 5\right)\tau^2 + \left(a_3^2b_3 - C\left(\beta^2\delta^2 - \beta^2\delta^2\right) + \beta + \delta + 5\right)\tau^3 + \cdots \\ -T_1\tau c_1 - 2T_1\tau^2c_2 - 3T_1\tau^3c_3 - \cdots &= \left((C(1/\alpha\beta) - \beta\delta\sqrt{C(1/\alpha\beta} + Cc_1^2\cos\theta\right)\tau + \left((C(/\alpha\beta) - \beta\delta\sqrt{C(1/\alpha\beta} + Cc_2^2\cos\theta\right)\tau^2 + \left(k(C(1/\alpha\beta) - \beta\delta\sqrt{C(1/\alpha\beta} + Cc_3^2\cos\theta\right)\tau^3 + \cdots \end{aligned} \tag{10}$$

We have developed Matlab code to analyze the system stability and sensitive dependence on initial condition (Figure 2(a)). The system has two same connected points with quadratic curve and one-saddle focus-nodes that can calculate plasma behavior of a particular orbital motion with interval $h = [-0.02\text{–}+0.02]$. Figure 2[(b.a & b.b) and (c.a & c.b)] presents the system with real time values and sensitive dependence x, z-direction effected by external force 'sin (θ)' for the purpose to control the plasma behavior under two conditions. It depends on the control parameter 'e' with limited range of parameters, that is, 0.018–0.009 and 0.4–0.1 turbulence, behavior of perturbation, particle distribution function, and accuracy of the system. It is convenient to analyze the steady state condition and sensitive

Comparison of τ

$$\begin{bmatrix} -T_1 + 0.02\cos\theta & 0 & 0 \\ 0 & -T_1 - 0.01 & 0 \\ 0 & 0 & -T_1 \end{bmatrix} \begin{bmatrix} a_1 \\ b_1 \\ c_1 \end{bmatrix} = 0 \tag{11}$$

$$\left\{ \begin{array}{l} a_1 = \theta_1 \\ b_1 = (-\beta - \delta - 5)\theta_1 \\ c_1 = (0.2 - \beta\delta)\theta_1 \end{array} \right. \tag{12}$$

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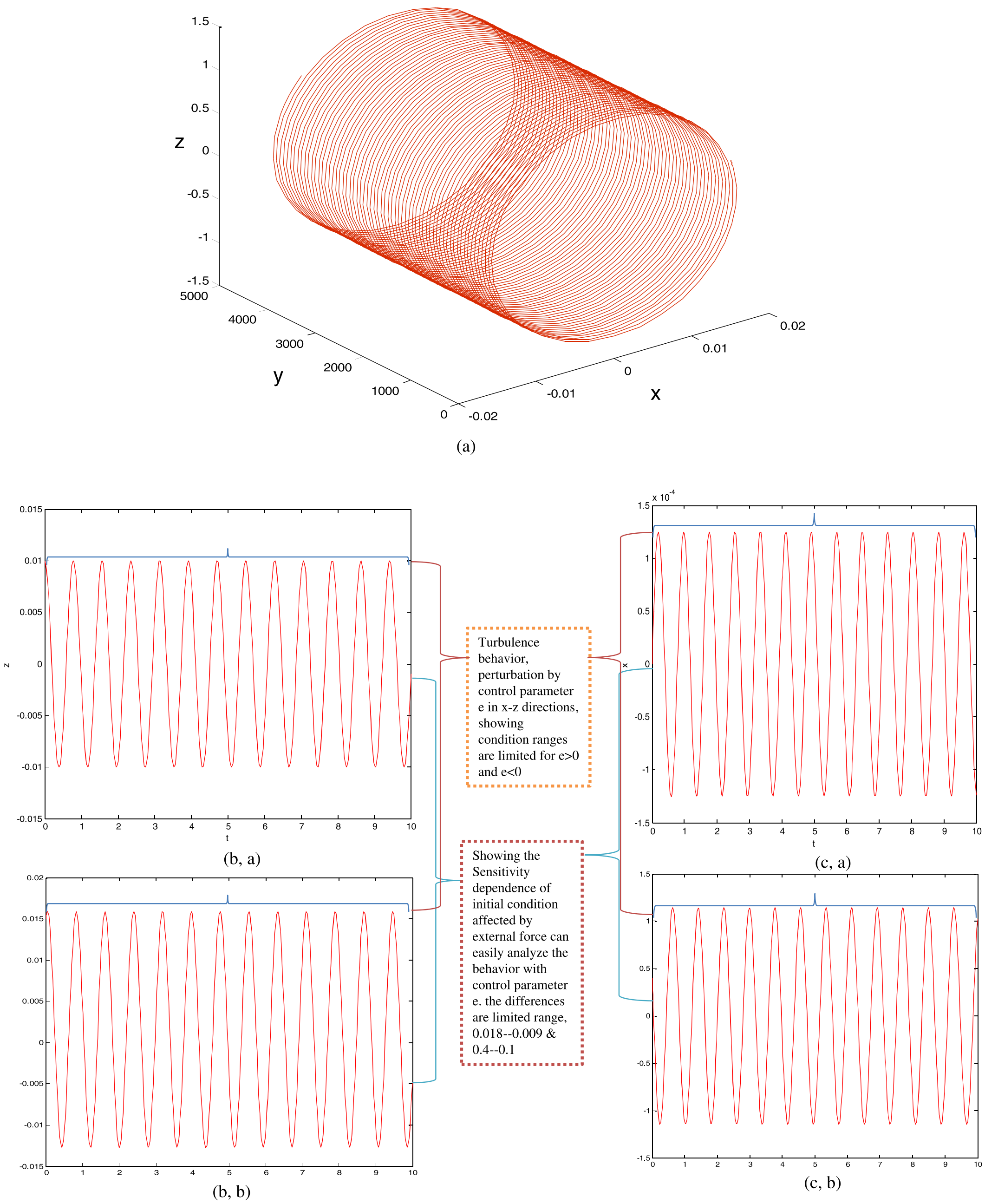

Figure 2. Three dimensional view of the system, plasma dynamical behavior with time interval, stability, and control parameters.

$$\begin{bmatrix} -2a_1\alpha\cos\theta & 0 & C \\ 2a_1b_1 & a_1^2 & -2Cc_1 \\ 2a_1k-\beta\delta & 0 & 2Cc_1\cos\theta \end{bmatrix} + \begin{bmatrix} a_1 \\ b_1 \\ c_1 \end{bmatrix} = \begin{cases} x(t) = +\sqrt{C(1/\alpha\beta + \theta_1 e^{-t})} \\ y(t) = +\sqrt{C(1/\alpha\beta)} + (-\beta-\delta-5)\theta_1 e^{-t} \quad t<0 \\ z(t) = +\sqrt{\beta^2\delta^2-\beta^2\delta^2} + (0.2-\beta\delta)\theta_1 e^{-t}, \\ x(t) = -\sqrt{C(1/\alpha\beta)} + \theta_2 e^{t} \\ y(t) = -\sqrt{C(1/\alpha\beta)} + (-\beta-\delta-5)\theta_2 e^{t} \quad t>0 \\ z(t) = -\sqrt{\beta^2\delta^2-\beta^2\delta^2} + (0.2-\beta\delta)\theta_2 e^{t} \end{cases} \tag{13}$$

Coupling of total force on the vessel, interaction forces, and vertical-radial forces in plasma system (A) matrix gives

Because $\theta_1 = \theta_2 = \pm 1$ are free parameters and have same connected points as P^+ and P^-. For this reason, plasma dynamical behavior of tokamak perfectly analyzed all aspects (before and after disruption), initial interaction between the forces, and VDE downward calculation of the halo current analysis, which is the great achievement in EAST tokamak.

The results with details are covered in 'result and analysis' section.

4. PLASMA VERTICAL DISPLACEMENT ORIENTATION MODEL

We have applied this system of equation (A) in the tokamak device and observed that when the plasma moves to lower state, it received downward forces from the radial component of magnetic field for plasma elongation, which accelerates downward motion.

The balancing forces acting on the plasma are $F_{side,\,bal1}$ and $F_{side,\,bal2}$
where

$$F_{side,\,bal\,1} = \frac{1}{2}.B_{tor}\left(R_p - a_p\right).I_{halo}.\mu_{shift.peak} \tag{14}$$

By system (A), the vertical displacement of the plasma in downward direction is slower than the upward movements. In this case, when the plasma flows into the vacuum vessel through in-vessel components, halo current produces large values of J X B forces acting on the vessel through in-vessel components [15]. By system (A) matrix, the halo current analysis for downward vertical displacement is 6.57 MA, while some other tokamak has different analysis such as 6.6 MA in International thermonuclear experimental reactor (ITER) [16,17]. This value is obviously greater than the upward movements, which clearly indicates the shrinking volume of plasma. Consequently, the balancing forces seem higher too. The addition of halo current on either sides is higher as it has been added together at the boundaries and cancel the effect of each other at the central position. It has been cleared in Eq. (14) that the plasma current has been generated at the center of plasma at a distance 'a_p' from the vessels and exchange current flow along the length of the plasma. This vertical component gives poloidal flow path resulting into the radial forces interacting with toroidal field. This field generates balancing sideways forces to the plasma named as $F_{side,bal2}$,

where

$$F_{side,bal2} = \Pi.B_{tor}.a_p.\delta I_{p,1,\max} \tag{15}$$

In case of downward direction of plasma, the poloidal flow path $\delta I_{P,1}$ can be due to divertor and not purely vertical as well.

$$F_{side,bal1,VDEdown} = \Pi.B_{tor}.a_p.\delta I_{p,1,\max} \tag{16}$$

During this phenomenon, thermal quenching took place in a shorter time compared with vertical resistive plasma motion, induced eddy currents in the upper and lower parts of the plasma surrounding structures. At this stage, the plasma may have upward as well as downward direction depending upon the forces acting upon. Further variation in the poloidal current has been observed in the passive structure as an outcome of toroidal flux. Poloidal halo current flows outside the closed flux halo surface generated by the compression of the toroidal flux within the plasma as it moves towards the vessel. This halo current generates an upward force on the plasma and decelerates the downward plasma. Meanwhile, poloidal halo current flows outside the last closed flux surface induced by the compression of toroidal flux within the plasma as it moves towards the vessel. This poloidal halo current establishes upward force on the plasma and decelerates the downward plasma movement. The halo region intercepts the vessel, and current will flow into the vessel, which generates the downward vertical force. The vertical force on the plasma and the vessel due to halo current is generated by coupling between toroidal magnetic fields and are of exactly same magnitude but in opposite direction. Hence, reaction forces on the toroidal coil exactly cancel out, and no net force acts on toroidal field coil during VDEs. Therefore, total force on the vessel would be the sum of forces because of halo current and eddy currents, that is,

$$F_h + F_{p,v} + F_{p,c} = 0 \tag{17}$$

Thus, the reaction force acts only on the poloidal field coils, and total interaction of eddy current and halo current are

$$F_{eddy} + F_{v,h} = F_{p,c} + F_{v,c} = F_v^{total} \tag{18}$$

Therefore, the total force on the vessel is expressed as

$$F_{eddy} + F_{halo} = F_{eddy,halo}^{total} \tag{19}$$

Finally, total vertical and radial forces can be written as

$$\sum_{i=-2.3}^{4.0} Fv_i + \sum_{j=-0.7}^{142} F_{rj} = \sum_{i=-2.3,j=-0.7}^{4.0,142} F_{v_i,r_j}^{tolal} \tag{20}$$

Initial interaction between the forces can be written as

$$I(t) + B(t) = I_0 + B_0 + \Delta(I(t) + B(t)) \tag{21}$$

$$I(t) + B(t) - \Delta(I(t) + B(t)) \tag{22}$$

$$I(t) + B(t)[1 - \Delta] = I_0 + B_0 \ \ (initial \ \ state) \tag{23}$$

The absolute variations can be assumed in first approximation invariant for all cases.

5. RESULT AND ANALYSIS

We have developed a numerical model that perfectly examines the plasma behavior under specific conditions. The behavior of perturbation, initial interaction between the forces, plasma turbulence, and stability data limitation

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Table II. Numerical results of individual essential aspects to examine the plasma behavior of tokamak.

No.	Plasma tilting and static position behavior in case of β, α arbitrary parameters with time interval by system (A)			Scaling factor (E, H-VDE)	Absolute delta (I[MA])	Initial interaction between the forces		
	$h = [2E+03, 4.21E+04]$					$\Delta = \lvert RK5_{0.01} - RK5_{0.001}\rvert$		
	$\Delta x_{\beta,\alpha}$	$\Delta y_{\beta,\alpha}$	$\Delta z_{\beta,\alpha}$	$K_{e,h}$	$\Delta I[MA]$	$\Delta x_{I_0+B_0}$	$\Delta y_{I_0+B_0}$	$\Delta z_{I_0+B_0}$
1	1.31 E + 05	1.7E + 05	2.31E + 05	1.12	0.9	−2.69E + 03	−2.45E + 03	−2.55E + 03
2	8.76E + 05	4.49E + 05	7.22E + 06	1.28	2.0	2.75E + 05	2.82E + 05	2.79E + 05
3	5.28E + 05	4.52E + 05	1.75E + 06	1.00	2.6	2.79E + 05	2.8E + 05	2.8E + 05
4	3.65E + 05	1.79E + 05	1.56E + 06	2.00	1.4	2.79E + 05	2.79E + 05	2.79E + 05
5	1.96E + 05	6.2E + 04	6.35E + 04	1.2	0.6	2.79E + 05	2.79E + 05	2.79E + 05
6	1.04E + 06	3.37E + 05	4.9E + 04	1.10	0.8	2.78E + 05	2.78E + 05	2.79E + 05
7	5.67E + 05	7.19E + 05	2.94E + 04	1.14	1.0	2.79E + 05	2.79E + 05	2.79E + 05
8	2.68E + 05	8.93E + 05	6.01E + 04	1.11	1.2	2.78E + 05	2.79E + 05	2.79E + 05
9	4.48E + 05	1.09E + 06	3.67E + 04	1.01	0.8	−8.76E + 03	−8.85E + 03	−8.8E + 03
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No.	Interaction forces, balancing sideways forces and vertical-radial forces in plasma system (A) matrix			Plasma turbulence behavior with time interval			Plasma behavior (EM/Plasma) (Shot #41195)	
	$h = [0.001 - 0.0001]$			$\Delta = \lvert ADM_{0.01} - ADM_{0.001}\rvert$			$t \in [0, 37]$	
	fx	*fy*	*fz*	Δx_τ	Δy_τ	Δz_τ	15[MA]	*IP*[*KA*]
1	−24.7	−28.8	−25.2	0.01	0.05	0.03	Start of plasma	0.030886
2	7.53E + 03	7.85E + 03	7.55E + 03	5.5E + 04	4.3E + 04	2.3E + 05	X-point formation	5.622277
3	−8.57E + 03	−8.75E + 03	−8.63E + 03	6.7E + 04	4.7E + 04	−5.7E + 05	Start of burn	14.95234
4	7.44E + 03	7.69E + 03	7.49E + 03	4.4E + 04	3.4E + 04	4.4E + 05	End of burn	16.79542
5	6.87E + 03	6.92E + 03	6.9E + 03	3.8E + 04	3.8E + 04	2.7E + 05	End of plasma	1.250000
6	−2.86E + 03	−2.95E + 03	−2.94E + 03	2.6E + 04	1.8E + 04	1.6E + 05	————	————
7	1.02E + 03	1.09E + 03	1.05E + 03	0.15E + 04	0.02E + 04	1.02E + 05	————	————

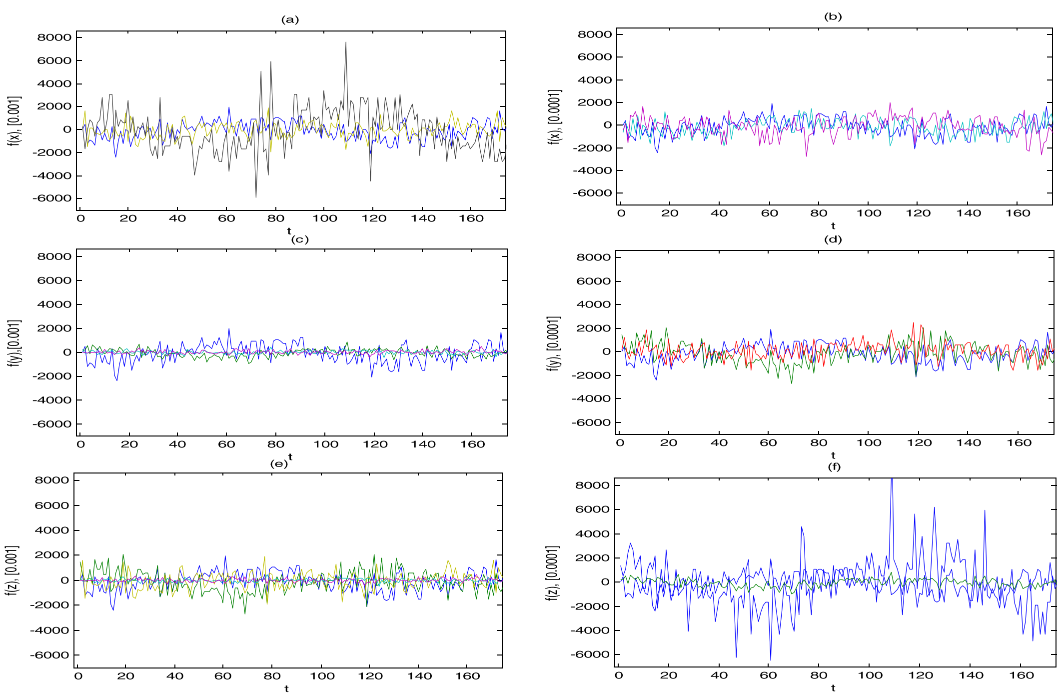

Figure 3. Matrix solution of system (A) have been coupled with interaction forces such as vertical-radial forces, vessel forces, and balancing sideways forces can be predict easily for the long pulse plasma.

Table III. Trends of plasma current with time by system (A) and Equation (13).

Plasma current (KA)	Time(10^4) seconds	Trends in plasma current
−2.96 E03	0–0.006	Plasma current initiated
2.75E05	0.6	Plasma disturbance
2.79E05	0.6–0.98	Attaining stability
2.79E05	0.98–35.50	Stable and sustain plasma
−8.76E03	35.50–36.05	Plasma quenched
−8.76E03	36.05–36.098	End of simulation

has been observed under iterative time steps. In our analysis, two time steps, that is, $\Delta t = 0.01$ and 0.001 allows calculating the plasma behavior, and this time, interval gives accurate simulation values as well. We used both explicit and implicit time steps methods applied in temporal discretization for the approximation of solutions of system (A). The parameters under this time ranges are listed in Table II.

In system (A), we have coupled matrix solution with interaction forces such as vertical, radial, balancing sideways forces, and vessel forces, which can easily analyze the plasma dynamical behavior. As illustrated in Figure 3(a–f), there is an oscillating behavior arisen from the turbulence and interaction of forces during the interval, that is, $h = [0.001–0.0001]$. In these figures, it is clear that the plasma current behavior is almost smooth within this range while Fx with $h = 0.001$ and Fz with $h = 0.0001$ have high oscillation between the interaction forces. This observatory shows that these asymmetric forces show the generation of halo current [18]. At this stage, plasma current is 0.3 ~ 0.5 MA, plasma density is $1.5 \sim 4.0 \times 10^{19}/\text{m}^3$, and time length of pulse is 10~100 s. The associated magnetic field lines around the current also denote the turbulence and varying behavior of plasma.

In Table III, the numerical results show that the plasma current starts from the initial values of −2.96E03 up to 0.6E4 s and then suddenly moves to high values, that is, 2.75E05, which denoted the plasma high current values at the start of burn (14.9534 IP[KA]). At this stage, the current gets down to 0.04E05 values and reaches to the values 2.79E05 in less than 1 s duration. 2.79E05 is the end of burn plasma stage (16.79542 IP[KA]). The plasma current remains the same for about 34.50 s and then suddenly gets down to very low values, that is, −8.76E03, which is even lesser than the initial point. It happened because the plasma has been quenched at 36.098 s. Figure 4 shows the graphically results by software techniques. Over 30 s H-Mode (SN#41195) and over 400 s long pulse plasma (SN#43336) have been noted in EAST tokamak [5]. EAST could play a key role for long pulse high performance plasma operation for ITER within next 5 years.

In Table II, plasma dynamical behavior solution in case of $\beta = 8$ and α is arbitrary, $\alpha = 0.1$ and β is arbitrary, and $\beta = 8$ and $\alpha = 0.1$ by using mathematical model (A) with interval $h = [2\text{E}+03–4.21\text{E}+04]$ shown the interaction between the forces and magnetic field of circle current loop. In Figure 5, it can easily analyze the blue line plasma current variation, green line halo current variation, and red line Electromagnetic field force (EMF). The interaction between blue and green lines perfectly goes smoothly (especially point A to B goes

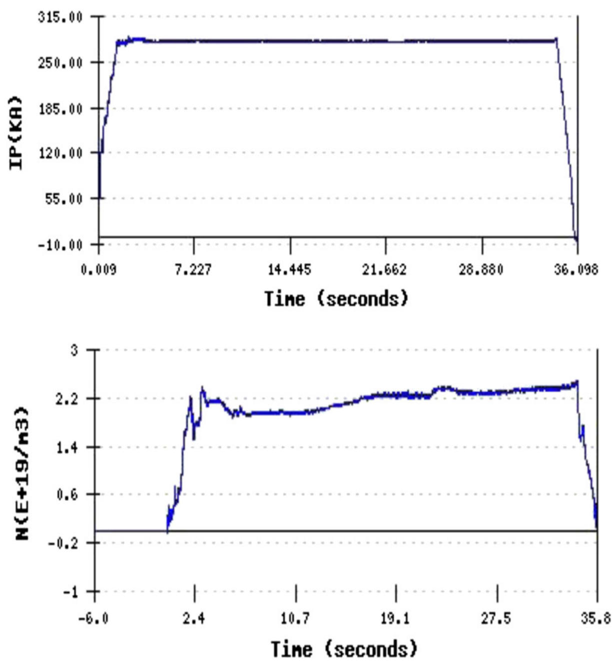

Figure 4. Shown the perfect smooth plasma sustain time and sufficient range (up), shown the plasma density (down).

Int. J. Energy Res. 2016; **40**:497–506 © 2015 John Wiley & Sons, Ltd.
DOI: 10.1002/er

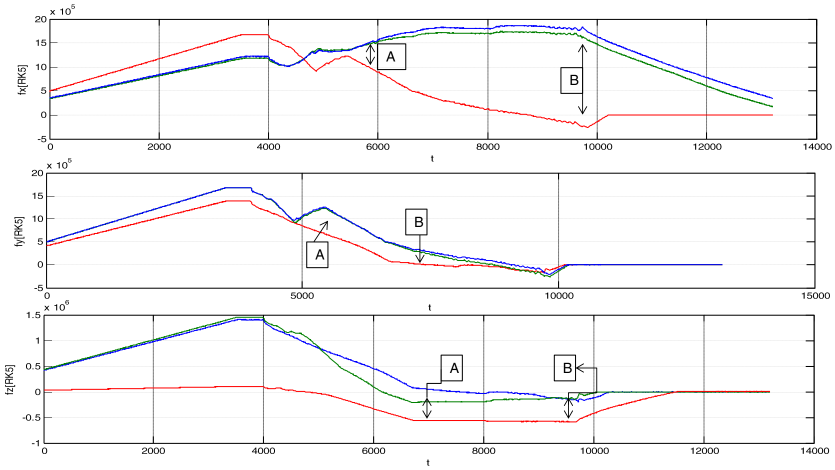

Figure 5. Plasma dynamical behavior solution in case of $\beta = 8$ and α is arbitrary, $\alpha = 0.1$ and β is arbitrary, and $\beta = 8$ and $\alpha = 0.1$ by using numerical techniques with interval $h = [2E + 03\text{–}4.21E + 04]$.

perfectly with small turbulence), while the red line makes some disturbances (decreasing and increasing in middle and down figure) in three cases in 2000–4000 ms and 6000–10000 ms. This behavior shows the change of magnetic field points during VDE down and changing of flux, which are more convenient in order to discuss the static and tilting position of plasma behavior [19,20].

6. CONCLUSION

The developed nonlinear plasma system (A) justifies a sound way to theoretically discuss the dynamical behavior of the main plasma characteristics under controlled conditions. This system (A) can exactly calculate the magnetic field change points during VDE down and variation in flux. The developed system is more convenient to discuss the static and tilting position of plasma behavior that depends on alpha and beta arbitrary parameters. Similarly, plasma dynamical model can exactly control and calculate plasma VDE to analyze the interaction forces of halo current. The model also provides the perfect and smooth plasma sustains time by numerical techniques. This model can be extended to predict other related parameters of tokamak reactor, which is a very important field of research. The applicability of this system includes predictive values and justification of the experimentation in tokamak reactor. This is a novel model to open theoretical grounds for fusion technology research.

NOMENCLATURE

$A(m^2)$	= Plasma area
ap (m)	= length from center of plasma
α	= Indicates the plasma tilt position
B(T)	= Total magnetic field (*x*,*y*,*z*-direction)
$B_{initial}$(T)	= Initial magnetic field
B_θ(T)	= Poloidal magnetic field
B_ϕ (T)	= Toroidal magnetic field
β	= Every 30° cross section of whole plasma
e	= Control parameter
I_p(MA)	= Plasma current
J_ϕ(e/m3)	= Plasma density
K(m)	= Elongation
$K_{e,h}$	= Scaling factor (E,H-VDE)
R_p(m)	= Major radius
W(MJ)	= Plasma energy
$\delta I_{p,1}$	= Poloidal flow path
δ	= Triangularity

ACKNOWLEDGEMENTS

The research team showed their gratitude and sincere appreciation to Tokamak Design Division, Institute of Plasma Physics (ASIPP) and Chinese Academy of Sciences President's International Fellowship Initiative for funding and supported this research. The research has been covered under grant No. 2014GB101001 from China National Special Magnetic Confinement Fusion Science Program. Moreover, First author appreciate contribution by Dr. Salah U. D. Khan for visiting and solving the technical issues of the research through research group no RGP-VPP-255 supported by Deanship of Scientific Research at King Saud University.

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