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Research Article

Direct Method-Based Transient Stability Analysis for Power Electronics-Dominated Power Systems

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With the extensive application of power electronics interfaced nonsynchronous energy sources (NESs) in modern power systems, the system stability especially the transient stability is prominently deteriorated, and it is crucial to find a comprehensive and reasonably simple solution. This paper proposes a direct method-based transient stability analysis (DMTSA) method which concludes the key steps as follows: (1) the system modeling of Lyapunov functions using mixed potential function theory and (2) the stability evaluation of critical energy estimation. A voltage source converter- (VSC-) based HVDC transmission system is simulated in a weak power grid to validate the proposed DMTSA method under various disturbances. The simulation results verify that the proposed method can effectively estimate the transient stability with significant simplicity and generality, which is practically useful to secure the operation and control for power electronics-dominated power systems.

1. Introduction

At present, NESs such as renewable power generation, flexible AC transmission systems, HVDC transmission systems, energy storage devices, and DC microgrids are increasingly widely employed in power systems [1–5]. Under the considerable NES penetration, the system dynamic characteristics can potentially deviate from those of the traditional AC power system. To contain system transient instability issues such as short-term frequency variations and voltage fluctuations is a major challenge for system operators [6, 7]. In addition, in Europe and America, with the development of power electronics-dominated power system, it inevitably brings some problems to the system, such as the complexity of design in some devices, difficulty in setting the parameter of relay protection [8], difficulty in system stability and limit analysis [9], harmonic suppression and reactive power compensation [10], and so on. By virtue of fast-switched power electronics, NES possesses an enhanced controllability of the system and can potentially improve the transmission performance of the system. Compared with the traditional AC power system, the topology of the power electronics power system changes with the switching action of the power and electronic devices, and the whole system has multiple time-scale control interactions. In addition, strong nonlinearity and dynamic characteristics exist in power electronic converters, and modulation and limiting phenomena occur when using pulse width modulation (PWM) which has saturation nonlinearity. These characteristics will seriously affect the stability of the power electronics-dominated power system.

Stability issues associated with NES are classified into three levels based on their scales: device level which relates to the control and operation of the device itself; subsystem level which deals with small-scale NES-dominated systems such as microgrid, ship, and aircraft electrical systems; and the power grid level which includes generation, transmission, and distribution [11]. A lot of research studies have been done for small signal stability analysis of power electronics-dominated power system (PEDPS). In [2], a detailed mathematical model of multiterminal transmission system based on VSC (voltage source converter) is established, and the small signal stability of the hybrid network is studied by using eigenvalues and the associated participation factor

matrix. Zeng et al. and Zhang et al. [12, 13] introduced existing small signal stability analysis methods specific for microgrid applications, and the key affective parameters were determined. However, these methods can only judge the stability of the system near the steady working point and cannot evaluate the boundary of the system stable region and the stability margin around the equilibrium point [11]. It is difficult to comprehensively analyze the stability of the system, so it is necessary to study the transient stability of the power electronics-dominated power system.

In the aspect of transient stability analysis of power electronics-dominated power systems (PEDPS), three methods are mainly used—time domain simulation method [14–16], artificial intelligence method [17–19], and direct method [20–22]. Baharizadeh et al. [15] analyzed the proposed control strategy for hybrid microgrids based on the time domain simulation method and studied the large signal stability of the system. In [16], three kinds of transient stability simulation models for multiterminal VSC-MTDC transmission system are studied and tested by the time domain simulation method, and the accuracy and speed of the model are compared. In [23, 24], the large disturbance stability problem of more electric aircraft power systems under generator failures and load sudden changes is studied by time domain simulation. As the most mature and reliable method, time domain simulation is often used as a standard to check other methods but is difficult to be directly used for online stability analysis. As the order of power system state variables increases, the amount of computation in time domain simulation will be greatly increased. In addition, time domain simulation method can only qualitatively judge whether the system is stable but cannot get quantitative information such as stability margin of the system. It lacks guiding significance for the engineering design.

Olulope et al. [18] applied artificial neural network to the transient stability analysis of hybrid distributed generation system and predicted the critical clearing time of the system. Balu et al. [25] presented a power system transient stability assessment method based on composite artificial neural network composed of Kohonen network and some radial basis function (RBF) networks, in which the training time was short and the classification was high. In the transient stability analysis of the power system, the artificial neural network method mainly takes the functions of data preprocessing and postprocessing and has the characteristics of fast and intuitive computation [17–19, 25]. However, when the actual data are not consistent with the presupposed data during the analysis process, the application of artificial neural network can cause difference between the analysis result and the actual stability index.

Griffo and Wang [21] used the direct method to analyze stability of an electric aircraft power system under large disturbances, and the effectiveness of unstable boundary prediction is verified by experiment. Hu [22] proposed to analyze transient stability of power electronic converters by the direct method and designed the parameters of the device. When the direct method is applied to the transient stability analysis of power electronics-dominated power system, it can not only judge the stability of the system qualitatively but also get the stability margin of the system quantitatively. The advantages of direct method are: (1) considering nonlinearity and adapting to larger system with fast calculation (2) the stability can be directly judged by energy criterion, (3) giving the stability margin of the system. However, there are also limitations such as the construction of energy function is difficult and the judgment result is conservative in the detailed model of the system [22, 26].

To summarize, the system's differential algebraic equations are solved by the time domain simulation method to obtain the trajectory of the system state quantity changes with the number of generators over time. The main advantages are that the mathematical model is exhaustive, is of high reliability, and can adapt to large-scale power systems. However, the amount of calculation is large, the real-time stable control cannot be achieved, and information on the degree of system stability is not accessible. In the artificial neural network, the mathematical model is not necessary, and solving nonlinear equations is not required but fast recall speed is achieved. It can simulate arbitrarily complex nonlinear relations, but the instability mechanism of the system cannot be explored by the method. Once the system changes, all the data need to be reset, which is difficult to achieve in engineering practice. The direct method analyzes the stability of the system from the perspective of energy. Solving the Lyapunov equation to accurately judge the stability of the system is of great necessity but simulating the system's differential equations is not. Its prospect is the most promising due to the state stability analysis method, fast calculation speed, and the quantitative stability index provided. The direct method can quickly and effectively judge the stability of the system, and the insufficiency of the energy function construction can be solved by rational modeling and introducing the mixed potential function theory. Therefore, for a power electronics-dominated power system, the Lyapunov direct method is used to analyze its transient stability as well as to calculate the stability criterion and verify the simulation results in time domain.

In this paper, based on the direct method, an analytical method suitable for transient stability analysis of PEDPS is developed. Firstly, a Lyapunov function of the system is established by applying the mixed potential function theory; secondly, a detailed analysis procedure is presented; finally, the transient stability of a power system model incorporating a VSC-HVDC system is analyzed to verify the feasibility of this method. The method is proved to be a simplified analytical and a practical criterion for specific engineering design.

2. Transient Stability Analysis Process Based on Direct Method

As discussed in Section 1, PEDPS is a complex and fast time-varying nonlinear system with multiple time-scale controller interactions. Transient stability analysis using the direct method is to identify the mathematical dynamic model of a system, to derive its Lyapunov function, and to evaluate the stability criteria directly from the critical energy.

At first, the model for the power electronics-dominated power system analyzed must be determined under an appropriate approach [27]. The high penetration of different types of power electronics in one grid brings out various nonlinear properties such as controller delays and switching harmonics. The process of transient stability analysis based on a detailed system model is deemed to be very complicated. In addition, the proposed transient stability analysis of the direct method is not applicable for all nonlinear systems. Therefore, it is necessary to simplify the system model by theoretical analysis.

Secondly, the transient energy function, key to evaluate the stability of a dynamic system in the direct method, must be established. For a given system, Lyapunov defined a positive definite scalar function $P(x)$ as a fictitious generalized energy function to evaluate system stability by the sign of $\dot{P}(x) = \mathrm{d}P(x)/\mathrm{d}t$. For a given system, if a positive definite scalar function $P(x)$ can be found and $\dot{P}(x)$ is negative, then the system is asymptotically stable. $P(x)$ is called as Lyapunov function. This criterion is only a sufficient condition for evaluating the stability of system; i.e., if a Lyapunov function that satisfies the criteria is found, the system stability is assured; however, the system stability could not be denied if such function $P(x)$ is not found.

For a PEDPS with complex structure, its Lyapunov function usually cannot be obtained directly, so the system stability analysis is usually based on some approximation. At present, there are many ways to obtain suitable global Lyapunov function for various system elements, and approximations have to be applied onto system elements depending on the pursued detail levels. However, most methods cannot be well applied to some systems of special types, and oversimplified Lyapunov function may lead to conservative results [22]. Relying on the topological description of general nonlinear circuits, Jeltsema and Scherpen [28] proposed a mixed potential function method to deduce scalar functions. Moreover, these scalar functions in turn can be used to construct Lyapunov function to study the stability of those nonlinear circuits. The mixed potential function method is suitable for transient stability analysis of power electronics-dominated power systems. The basic idea is to establish the mixed potential function of P according to the system model at first, and then the Lyapunov function is established based on the stability theory of mixed potential function [29, 30].

Finally, the critical energy of the system is solved. The stability criterion can be obtained according to the Lyapunov function, while the critical energy is determined by stability criterion. In addition, for the sake of lower conservatism, the estimate value of attraction domain must be expanded as far as possible when solving the critical energy of the system. Moreover, in order to determine the accuracy of theoretical calculation value, after the theoretical stability criterion of the system is obtained by the direct method, this paper will combine time domain simulation experiment to test the stability domain results solved. Such a combination use of the direct method and time domain simulation method can greatly enhance the credibility of the results by taking advantages of both.

2.1. Identifying System Model. Different system models are selected for different analysis levels, and the resultant model must be reasonably and appropriately simplified. For transient stability analysis of PEDPS at the device level, detailed model of power electronic converter is often adopted, and power grid is simplified as an ideal power supply with impedance. For analyses at subsystem level or global power system level, it is necessary to establish a reasonable equivalent model for any converter [31].

2.2. Constructing a Model of Lyapunov Function

2.2.1. Introducing Mixed Potential Function. Firstly, establish a mixed potential function P [28], according to components and topological relations in a system, with a general form of

$$P(i,v)) = -A(i) + B(v) + D(i,v), \tag{1}$$

where i are v are inductor currents and capacitor voltages in the circuit, respectively, $A(i)$ and $B(v)$ are potential functions related to current and voltage, respectively, and $D(i,v) = i^T \cdot \gamma \cdot v$ is the energy of capacitor and part of a nonenergy storage element in the circuit in which γ is a constant coefficient matrix related to the circuit topology. Stability theorems of mixed potential function need to be used to obtain the stability criterion of the system under large disturbance if $A(i)$ is only related to some variables in $i_1, \ldots, i_r$, and $B(v)$ is only related to some variables in $U_{r+1}, \ldots, U_{r+n}$.

Secondly, verify the correctness of the function P by

$$\begin{aligned} L\frac{\mathrm{d}i_\rho}{\mathrm{d}t} &= \frac{\partial P}{\partial i_\rho}, \quad \rho = 1, 2, \ldots, r, \\ -C\frac{\mathrm{d}v_\sigma}{\mathrm{d}t} &= \frac{\partial P}{\partial v_\sigma}, \quad \sigma = r+1, r+2, \ldots, r+s. \end{aligned} \tag{2}$$

Establishing Lyapunov Function, let

$$\begin{aligned} P_i &= \frac{\partial P(i,v)}{\partial i}, \\ P_v &= \frac{\partial P(i,v)}{\partial v}, \\ A_{ii} &= \frac{\partial^2 A(i)}{\partial i^2}, \\ B_{vv} &= \frac{\partial^2 B(v)}{\partial v^2}. \end{aligned} \tag{3}$$

Then, a Lyapunov function of the system can be established as

$$P^*(i,v) = \frac{u_1 - u_2}{2} \cdot P(i,v) + \frac{1}{2}P_i^T \cdot L^{-1} \cdot P_i + \frac{1}{2}P_v^T \cdot C^{-1} \cdot P_v, \tag{4}$$

where L is the diagonal matrix of inductors, C is the diagonal matrix of capacitive elements, u_1 is the minimum eigenvalue of matrix $L^{-1/2} \cdot A_{ii} \cdot L^{-1/2}$, and u_2 is the minimum eigenvalue of matrix $C^{-1/2} \cdot B_{vv} \cdot C^{-1/2}$.

The differential form of this Lyapunov function is

$$\dot{P}^*(i,v) = \frac{\mathrm{d}P^*(i,v)}{\mathrm{d}t}. \tag{5}$$

If $P^*(i,v)$ is positive definite and $\dot{P}^*(i,v)$ is negative definite, then the system is asymptotically stable. However, this condition is only a sufficient condition for judging the stability of the system. Even if $P^*(i,v)$ is not positive and $\dot{P}^*(i,v)$ is negative, the system cannot be considered unstable. A Lyapunov function satisfying this condition can be established by further designed rational parameters.

2.3. Estimating Critical Energy

2.3.1. Solving Stability Criterion. The stability criterion of the whole system can be obtained by the precondition of system working in steady-state equilibrium operating points and the condition of working in transient stability, respectively.

The precondition of system working in steady-state equilibrium operating points can be solved by the equivalent circuit structure. The condition of working in transient stability, according to (4), is if all i, v in a circuit belong to a certain area, they satisfy

$$u_1 + u_2 > 0, \tag{6}$$

and if $|i| + |v| \longrightarrow \infty$, then

$$P^*(i,v) \longrightarrow \infty. \tag{7}$$

As $t \longrightarrow \infty$, all the solutions of the studied system will tend to steady equilibrium work point, and the system will eventually operate stably.

2.4. Determining Critical Energy. When $u_1 + u_2 = 0$, the system is critically stable, and the critical voltage $v_{\min}$ can be calculated. Taking $v_{\min}$ into the Lyapunov function (4), the critical energy of the studied system can be estimated as

$$P^*(i,v) = \min P^*(i, v_{\min}). \tag{8}$$

The concrete process of transient stability analysis based on the direct method is shown in Figure 1.

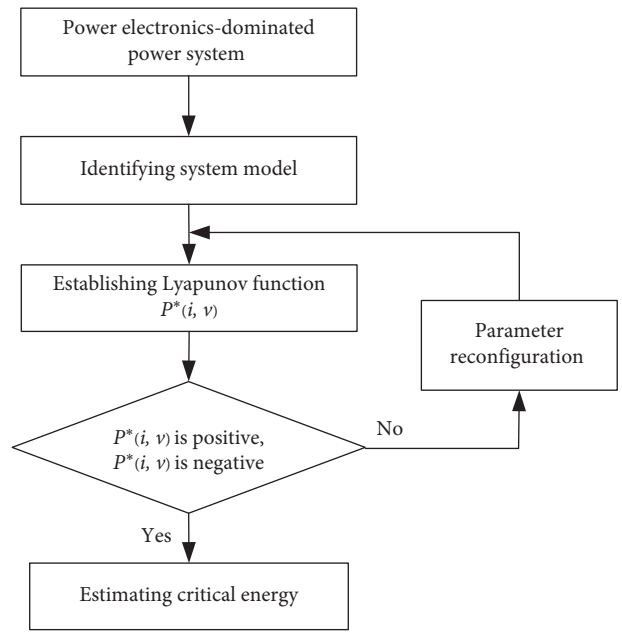

Figure 1: Concrete process of DMTSA based on the direct method.

3. Model Application of Direct Method onto a VSC-HVDC System

High-voltage direct current transmission system constructed by voltage source converter (VSC-HVDC) is a new type of DC transmission technology developed on the basis of full controlled power devices such as voltage source converter (VSC) technology, GTO, and IGBT. The VSC-HVDC system contains a large number of power electronics conversion devices, which can realize specific functions in the links of transmission, distribution, transformation, and utilization, and is a typical power electronics-dominated power system. A two-terminal VSC-HVDC system is shown in Figure 2, and we will analyze its transient stability according to the process proposed in the above section.

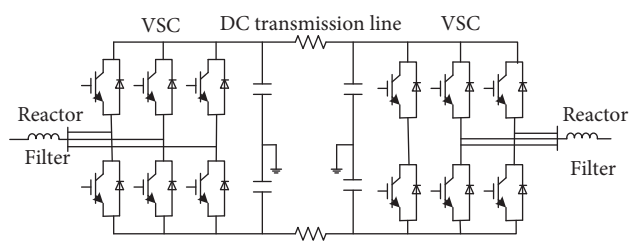

Figure 2: VSC-HVDC system.

3.1. Equivalent Model. It is supposed that the rectifier on the left part controls the DC voltage constant and the inverter on the right part controls the DC power constant. If the influence of the converter's switching characteristics is neglected, the controller's bandwidth is considered to be infinitely high, and the inverter has sufficient response speed. Then, the structure of this VSC-HVDC system can be simplified as an ideal circuit shown in Figure 3 [32].

In Figure 3, the rectifier is considered as an ideal voltage source, and v_{eq} is a DC output voltage; R and L represent the resistance and inductance of the DC line; and C represents the charging capacitance in DC side of the inverter. The controlled current source represents the inverter with a constant load of P_{cpl}. In the simplified circuit, although the RLC parameters are constant values, the circuit is still nonlinear due to the existence of the controlled current source.

3.2. Lyapunov Function. The state equation for the equivalent circuit shown in Figure 3 is

$$\begin{aligned} L\frac{\mathrm{d}i_L}{\mathrm{d}t} &= V_{\mathrm{eq}} - Ri_L - v, \\ C\frac{\mathrm{d}v}{\mathrm{d}t} &= i_L - \frac{P_{\mathrm{cpl}}}{v}. \end{aligned} \tag{9}$$

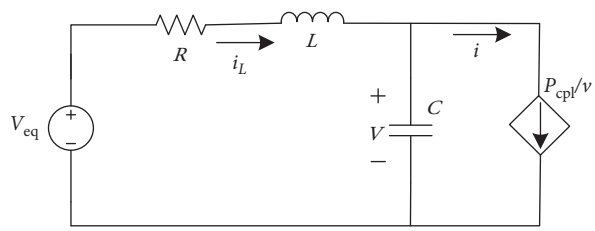

Figure 3: The simplified circuit of two-terminal VSC-HVDC.

The current potential function of the power supply voltage v_{eq} for nonenergy storage elements and resistance R is

$$A(i_L) = \int_0^{i_L} (-Ri_L)\mathrm{d}i_L + \int_0^{i_L} V_{eq}\mathrm{d}i_L. \tag{10}$$

The voltage potential function of constant load P_{cpl} for nonenergy storage elements is

$$B(v) = \int_0^{i} \frac{-P_{cpl}}{i}\mathrm{d}i = -\left(\frac{P_{cpl}}{i}\right) \times i + \int_0^{v} \frac{P_{cpl}}{v}\mathrm{d}v. \tag{11}$$

The energy of C is

$$D(i, v) = -\frac{i_L - P_{cpl}}{v} v. \tag{12}$$

Therefore, the mixed potential function of the whole circuit is

$$P(i_L, v) = -\frac{1}{2}R \cdot i_L^2 + \int_0^{v} \frac{P_{cpl}}{v}\mathrm{d}v + i_L \cdot \left(V_{eq} - v\right). \tag{13}$$

According to the model parameters shown in (13) and the circuit shown in Figure 3, we have

$$\begin{aligned} \frac{\partial P(i_L, v)}{\partial i_L} &= V_{eq} - Ri_L - v = L\frac{\mathrm{d}i_L}{\mathrm{d}t}, \\ \frac{\partial P(i_L, v)}{\partial v} &= \frac{P_{cpl}}{v} - i_L = -C\frac{\mathrm{d}v}{\mathrm{d}t}. \end{aligned} \tag{14}$$

Equation (14) satisfies the constraint conditions in (2), so the expression of the mixed potential function model is correct. Combined with the stability definition of the above mixed potential function, A_{ii} and B_{vv} are expressed as

$$\begin{aligned} A_{ii} &= \frac{\partial^2 A(i_L)}{\partial i_L^2} = \frac{\partial^2\left(1/2R \cdot i_L^2 - V_{eq}i_L\right)}{\partial i_L^2} = R, \\ B_{vv} &= \frac{\partial^2 B(v)}{\partial v^2} = \frac{\partial^2\left(-P_{cpl} + \int_0^{v} P_{cpl}/v\mathrm{d}v\right)}{\partial v^2} = -\frac{P_{cpl}}{v^2}. \end{aligned} \tag{15}$$

In the equivalent circuit, the equivalent inductance and capacitance are represented by only one inductance symbol L and one capacitance symbol C. Therefore, both $L^{-1/2} \cdot A_{ii} \cdot L^{-1/2}$ and $C^{-1/2} \cdot B_{vv} \cdot C^{-1/2}$ are first-order matrices, and their minimum eigenvalues are u_1 and u_2, respectively,

$$\begin{aligned} u_1 &= \min\left[\lambda\left(L^{-1/2} \cdot A_{ii} \cdot L^{-1/2}\right)\right] = \frac{R}{L}, \\ u_2 &= \min\left[\lambda\left(C^{-1/2} \cdot B_{vv} \cdot C^{-1/2}\right)\right] = -\frac{P_{cpl}}{Cv^2}. \end{aligned} \tag{16}$$

According to (3), (13), and (16), the global Lyapunov type function of the system can be deduced as

$$\begin{aligned} P^*(i_L, v) = {} & \frac{1}{2}\left(\frac{R}{L} + \frac{P_{cpl}}{Cv_{min}^2}\right) \cdot P(i_L, v) + \frac{1}{2L}\left(V_{eq} - Ri - v\right)^2 \\ & + \frac{1}{2C}\left(\frac{P_{cpl}}{v} - i\right)^2, \end{aligned} \tag{17}$$

and its differential equation is

$$\begin{aligned} \frac{\mathrm{d}P^*(i_L, v)}{\mathrm{d}t} = {} & \frac{1}{2}\left(\frac{R}{L} + \frac{P_{cpl}}{Cv_{min}^2}\right) \cdot \frac{\mathrm{d}P(i_L, v)}{\mathrm{d}t} + \frac{1}{L} \cdot \left(V_{eq} - Ri - v\right) \\ & \cdot \left(-\frac{\mathrm{d}v}{\mathrm{d}t} - R\frac{\mathrm{d}i}{\mathrm{d}t}\right) + \frac{1}{C}\left(\frac{P_{cpl}}{v} - i\right) \cdot \left(-\frac{P_{cpl}}{v^2} - \frac{\mathrm{d}i}{\mathrm{d}t}\right). \end{aligned} \tag{18}$$

The 3D graph of this Lyapunov function is shown in Figure 4, and the contour lines of its differential values are shown in Figure 5.

As can be seen from Figures 4 and 5, the Lyapunov function of the system is positive within a large range near the equilibrium point, and the derivative $\mathrm{d}P^*(i_L, v)/\mathrm{d}t < 0$ is negative. Therefore, the system is asymptotically stable according to Lyapunov stability theorem.

3.3. Stability Criterion and Critical Energy. According to Figure 3, the steady-state equation is

$$\begin{aligned} i &= \frac{P_{cpl}}{v}, \\ v &= V_{eq} - Ri_L. \end{aligned} \tag{19}$$

As shown in Figure 6, curves 1 and 2 are the characteristic curves of power supply and load in the system, respectively. Curve 2 moves to curve 3 or curve 4 as the voltage rises or decreases slightly. The equilibrium working point of the system can be obtained when the power supply current equals to the load current, i.e., the intersection points of A and B [33]. An equilibrium working point is said to be stable if the system at that point can restore steady state under small disturbance. Obviously, in Figure 4, point A is not a steady-state equilibrium working point but point B is.

From equation (19), the voltage and current of the system at point B are

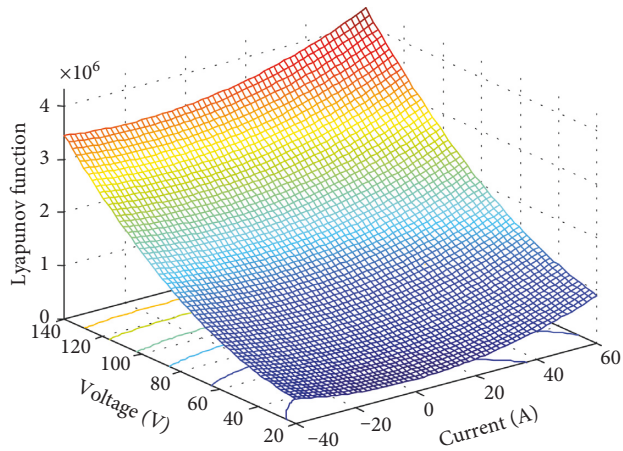

Figure 4: The three-dimensional diagram of Lyapunov function.

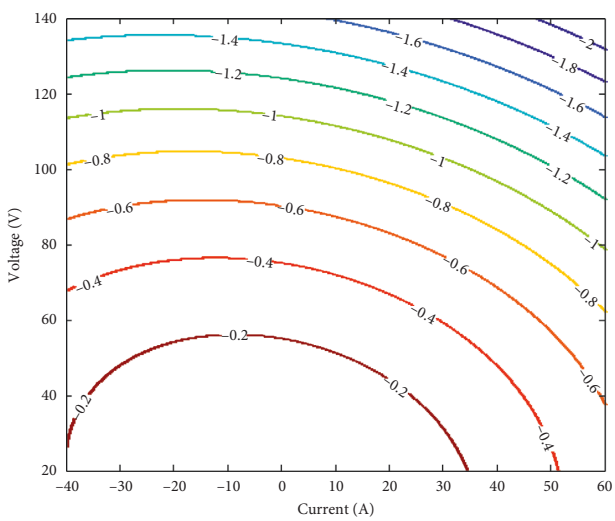

Figure 5: The contour lines of $dP^*(i_L, v)/dt$.

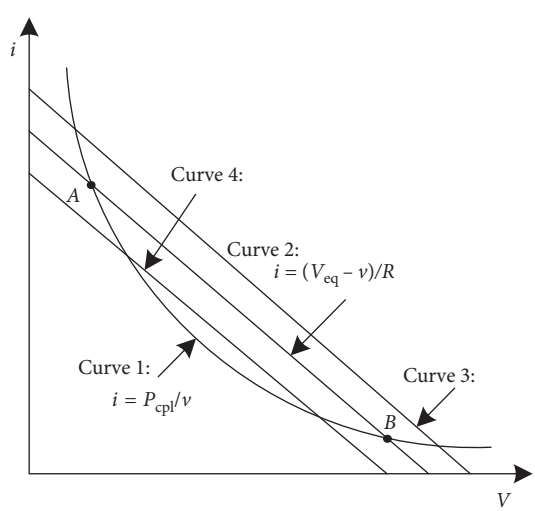

Figure 6: The source and load characteristic curves of a two-terminal VSC-HVDC system.

$$v = \frac{V_{eq}}{2} \pm \sqrt{\left(\frac{V_{eq}}{2}\right)^2 - RP_{cpl}},$$
$$i_L = \frac{P_{cpl}}{v}. \tag{20}$$

For the two-terminal VSC-HVDC system, if $(V_{eq}/2)^2 - RP_{cpl} < 0$, the voltage v is plural and the system is unstable. The system is in a state of critical stable state when (19) has only one real number solution. Therefore, for the two-terminal VSC-HVDC system, one of the necessary conditions for the system to work in steady state is $(V_{eq}/2)^2 - RP_{cpl} > 0$ or

$$R_{max} < \frac{V_{eq}^2}{4P_{cpl}}. \tag{21}$$

Formula (21) gives the criterion of the steady-state equilibrium working point, which describes the relationship between the equivalent supply voltage, the equivalent resistance, and the constant load power, and is also the precondition for the stability of that system.

In addition, based on the stability theorem of the above mixed potential function, formulas (6) and (16), the sufficient condition for the system to be in transient stable state is

$$R > \sqrt{\frac{L}{C}} = R_{min}. \tag{22}$$

Based on equilibrium point determination and mixed potential function theory, the stability criterion of the system shown in Figure 3 is

$$\sqrt{\frac{L}{C}} < R < \frac{V_{eq}^2}{4P_0}. \tag{23}$$

In addition, when the system is critically stable, $u_1 + u_2 = 0$, so

$$u_1 = -u_2 = \frac{R}{L} = \frac{P_{cpl}}{Cv^2}. \tag{24}$$

And the critical voltage is

$$v_{min} = \sqrt{\frac{P_{cpl} \cdot L}{C \cdot R}}. \tag{25}$$

By substituting equation (25) into the Lyapunov function (16), the critical energy of the system is

$$P^*(i_L, v) = \min P^*(i_L, v_{min}). \tag{26}$$

3.4. Verification of Simulation Results. In order to verify the credibility of theoretical calculation results based on the direct method proposed in this paper, detailed time-domain simulation experiments are carried out in the MATLAB environment.

The setting parameters of the equivalent circuit shown in Figure 3 are shown in Table 1.

Table 1: Equivalent circuit parameter setting.

Parameter	Value	Units
V_{eq}	100	V
F	400	Hz
L	3	mH
C	3000	μF
R	0.16	Ω.
P_{cpl}	1000	W

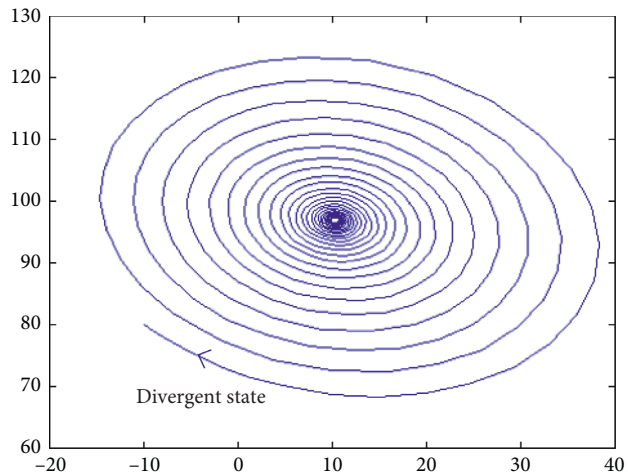

Figure 7: State space trajectory.

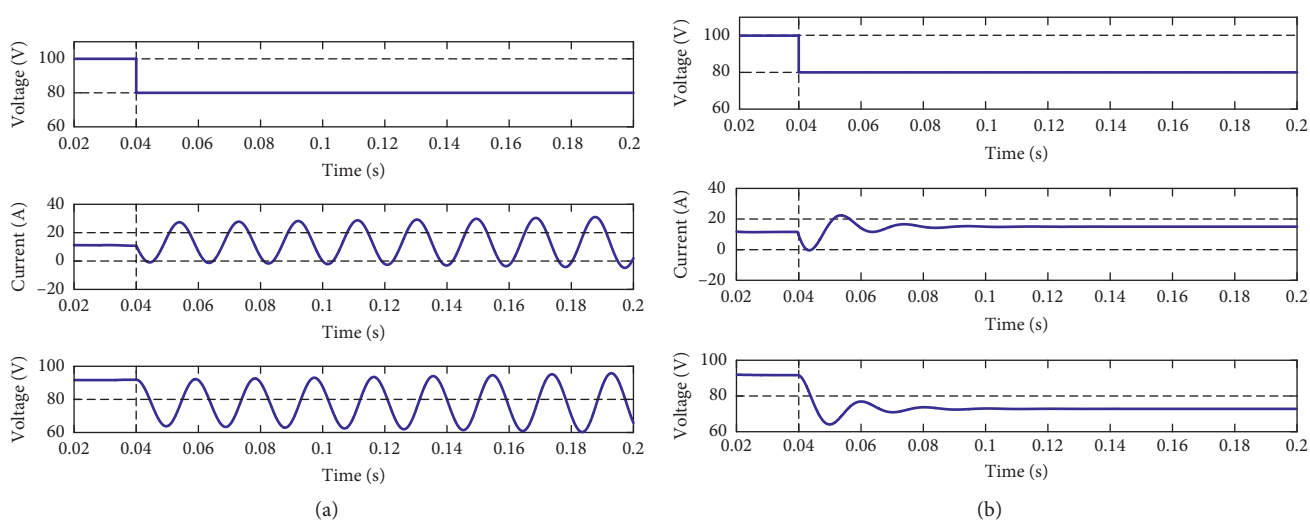

Figure 8: Time domain simulation results.

According to (20) and (25), a steady-state equilibrium point of the two-terminal VSC-HVDC system is (98.4 V, 10.2 A), and v_{min} is 79.1 V. It is assumed that the DC control voltage of the rectifier is reduced from 100 V to 80 V after 0.04 seconds. At this time, with these parameters, the condition of (21) is satisfied, but (22) is not, so the system is unstable. The state space trajectory computed by using the mixed potential function theory is shown in Figure 7. It can be seen that the trajectory moves from steady equilibrium point to divergent state after a period of time, and the system is unable to keep stable at this time.

The time domain simulation results of the system stability after changing DC voltage are shown in Figure 8. When system parameters are not satisfied (19), the stability result is as shown in Figure 8(a), and the system becomes unstable after 0.04 seconds; when system parameters meet the requires (22), the stability results are as shown in Figure 8(b), and the system resumed stability after a period

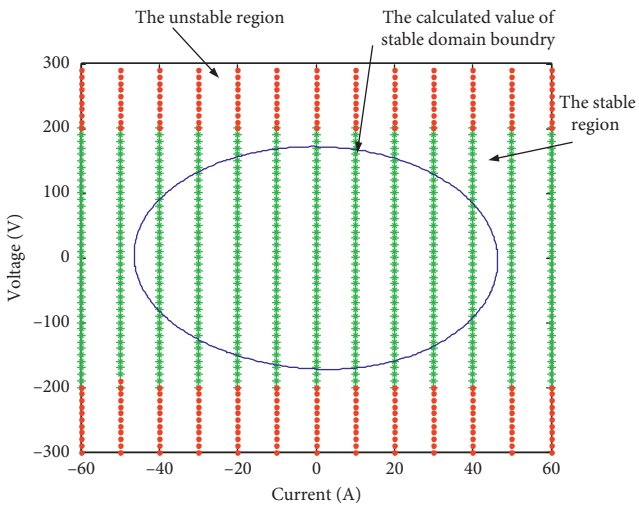

Figure 9: Critical energy estimation results.

of oscillation. Thus, the feasibility and accuracy of transient stability analysis of PEDPS by the direct method are also verified.

The numerical method is used to "explore" simulations when estimating the critical energy. The stability region of the system is solved by judging whether the initial points can converge to the equilibrium point, and the results are compared with the stable domain results calculated by the mixed potential function theory. The result is shown in Figure 9, in which the calculation results are moved to the origin for the convenience of observing the change range of the system variables. It can be seen that when the transient stability of the PEDPS is analyzed by the direct method, the estimated critical energy is conservative to some extent, but it can already cover the larger range near the equilibrium point. The result is very close to the large signal stability boundary of the system. In addition, compared with digital simulation, the computation time using the direct method is greatly reduced.

4. Conclusion

Compared with traditional power system, PEDPS is time-varying or non-autonomous, and its topology changes with switching actions of power electronic devices. In addition, each power electronic converter has the characteristics of structural complexity and saturation nonlinearity, which brings great difficulties to transient stability analysis of the whole system.

In this paper, based on the direct method and by introducing the mixed potential function theory, a complete set of transient stability analysis processes including system modeling, Lyapunov function construction, and critical energy estimation is proposed for the power electronics-dominated power system. In addition, a VSC-HVDC system is taken as an example for detailed transient stability analysis when a large disturbance occurs, and the stability criterion of the system is obtained. The analysis and simulation results show that the proposed process can be effectively applied to the transient stability analysis when large disturbance appears in the system. Furthermore, the introduction of mixed potential function theory also simplified the construction of the global Lyapunov function.

For the stability analysis of PEDPS with very complex structure, what we proposed in this paper is providing a set of simple and practical methods that could realize fast and accurate stability determination while avoiding complicated solving steps. Characterizing with simplicity and universality, such method provides not only reference value for the theoretical study of PEDPS transient stability analysis but also a practical stability criterion for specific engineering design.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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