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A Universal Model for Grid-Connected Converters Reflecting Power-Internal Voltage Characteristics

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Abstract—With the still increasing penetration of renewable energy, the power system is being more power electronics based and digital. The diversity of grid-connected power converters with various control strategies complicates the analysis of system dynamics, when various and detailed converter models are adopted. This paper thus proposes a universal model of grid-connected converters that can reflect the essential power-internal voltage characteristics. With that, the diversity of converter outer controllers may be discarded, as their dynamics can be represented by the deviation of active and reactive power. In the proposed model, the transfer functions from the converter output power to the internal voltage and to the Phase-Locked Loop (PLL) output frequency are obtained, enabling the exploration of the stability of the internal voltage and the PLL performance. An example system is adopted to demonstrate the proposed model and simulated in PSCAD/EMTDC. The results show that the model is accurate to reflect the impact of controller parameters on the power-internal voltage stability of the entire system.

Keywords—grid-connected power converter; modelling; internal voltage; external characteristics; power angle stability

I. INTRODUCTION

The current energy system is facing a revolution that the conventional coal-fired power generation is going to be replaced by the renewable energy generation, including wind energy, solar energy, geothermal energy, etc. The low (or even zero) carbon energy capture is transitioning the power generation into more environmental-friendly, where power electronic converters are irreplaceable as the connectors of distributed renewable power generation systems and large power grids [1], [2]. The power electronic-based interface enables a relatively flexible, reliable, and efficient energy conversion. However, with the continuous increase of renewable energy, a highly aggregated power electronic converter-based power system is emerging [3]. In this case, the static and dynamic characteristics of the entire system are significantly different from the conventional generation systems using rotational machines. It thus makes the analysis and control more complicated.

To explore and develop appropriate control and operation schemes, modelling the power converters is necessary, as a means of system analysis (e.g., stability issue). In the literature, certain attempts have been made into the modelling. For instance, a closed-loop interconnected model of an AC

connected multi-terminal DC (MTDC) system including open-loop voltage source converters (VSC) and open-loop MTDC systems was proposed in [4], where the modal analysis was employed to explore the small signal stability of the system. A small signal model of grid-forming converters was proposed in [5], enabling the determination of voltage and frequency droop gains for the system control. However, these models are suitable for the analysis of the single converter-based AC grid. When the number of converters increases, the above detailed models will burden the computational workload. Therefore, it calls for a simple but effective and universal model of grid-connected power converters, which can be aggregated in power electronic-based power systems.

It should be noted that the characteristics and dynamics of converters alter with the control objective changes. For instance, in a point-to-point VSC-based high voltage direct current (VSC-HVDC) system interlinking two large AC grids, one converter is responsible for the DC-link voltage stability and another should take charge of the power transmitting capacity [6]. It means that the primary control objective of the converters is to maintain the stability on the DC side in this case. On the contrary, in a distributed power generation system (DPGS) based AC grid, the converters may be connected to weak AC grids or remote-islanded generation units, which enforces the converters to operate with proper AC voltage and frequency control to support the AC side [7]. In certain cases, additional controllers for challenging demands like the DC-link voltage-active power coordinated droop control [8], active power-reactive power unified droop control are required to enhance the connection and operation [9]. With these control strategies, the dynamics of the power converters may interact with each other, complicating the modelling and thereby, also the analysis of the entire system, as aforementioned. Hence, in addition to simplicity, the diversity of control strategies should also be considered when modelling.

According to the response speeds of control loops, it is reasonable and meaningful to model the converters in multiple timescales, which is the common approach in the literature. For example, a model of a Doubly-Fed Induction Generator (DFIG)-based wind turbine system mimicking the synchronous generator in the DC-link voltage control timescale was presented in [10]. The concept was also used to model the grid-connected converters in [11]. Likewise, the model of grid-connected power converters in the AC current control timescale was given in [12], where the small signal stability analysis was performed as well. In this case, the main concept

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is based on the swing equation of the synchronous generator, and it provides the most information of power converters to AC grid, e.g., the relationship between the internal voltage and the converter output power. Although these models have not made a distinction of various control strategies (thus, the multiple timescales), the notion can be used with further modifications to exploit universal models.

In light of the above, this paper presents a universal model for grid-connected power converters, which can reflect the power-internal voltage characteristics. Consequently, it enables the stability analysis of highly aggregated converter-based power systems. The rest of this paper is organized as follows. Section II introduces the typical grid-connected converter system with various control strategies. It is discussed in Section III that the power-internal voltage analysis is straightforward for stability study, where the proposed model is detailed. In Section IV, a case study is carried out with the universal model, where simulations are performed to validate the analysis. Finally, concluding remarks are provided in Section V.

II. GRID-CONNECTED CONVERTERS

A. External Characteristics

In highly aggregated power converter-based power systems, the number of converters determines that the model of converter should be simplified for cost-efficient analysis. Thus, how simplified the model should be and what important characteristics must remain in the model are major challenges in such analysis.

In conventional multi-synchronous generator-based power systems, two of the most important stability issues include the power angle stability and voltage stability, which are in close connection with the active power and reactive power [13]. Further, the active power and reactive power determine the voltage phase and amplitude of the node, respectively, which reflects the operating state of the node. Hence, the relationship between the voltage and the power can represent the external characteristics of the power converter. The characteristics are also beneficial to the overall analysis of the power converter- and synchronous generator-based power systems.

For a synchronous generator, the power angle is the phase difference between the internal voltage and the terminal voltage. Accordingly, for a power converter, the output voltage and the voltage at the point of common coupling (PCC) after the line filter can be described by the internal voltage and terminal voltages [14]. Fig. 1 shows the universal model of the power converter reflecting external characteristics, where $E\angle\theta$ and $U_t\angle\theta_t$ are the internal voltage and terminal voltage of the power converter, respectively, $U_g\angle 0$ is the voltage of the AC grid infinite-bus as the reference, C is the DC-link capacitor and U_{dc} is the DC-link voltage, X_f and X_g are the equivalent reactances of the output filter and the grid, respectively, P , Q and P_g , Q_g are the output powers from the power converter and those injected to the PCC, and P_{in} is the input active power from DC sources.

B. Classification and Unification

To model power converters shown in Fig. 1 in a universal way, how to deal with different control strategies of power

Fig. 1. Grid-feeding converter-based AC grid.

converters is a challenge. The power converters connected to AC grids can be classified according to the control objectives and the ways in which they share the power to the grids. Generally, in the DPGS, the power converters can be divided into three main types—grid-feeding, grid-supporting, and grid-forming converters, corresponding to three control strategies for the system [15].

Whatever the control strategy of the power converter is, the controller can generally be divided into two cascaded loops. The outer control loops are responsible for the DC-link voltage, active and reactive power, frequency, etc., and provide the AC current reference to the inner controllers. The inner controllers regulate the AC current, which are almost the same in power converters for various control objectives [16]. It can thus be inferred that the universal model can be modular-based, where the modules correspond to the control loops. The module of the inner control loops and PLL can be similar and the module of the outer control loops differs with the control strategies.

A universal model of the grid-connected converters is exemplified in Fig. 2, where $\hat{i}$ is the AC current flowing through the filter, L_f is the filter inductor, θ_p is the output voltage phase of the PLL, the superscript “*” denotes the reference value, the subscripts (d and q) denote the values decomposed into the dq -frame based on the PLL output voltage phase. In Fig. 2, the active power and reactive power outer controllers are demonstrated, and they can be replaced to others like the DC-link voltage controller or terminal voltage controller upon demands. In agreement with specific assumptions, the dynamics of the DC-link voltage, frequency, and terminal voltage amplitude can be represented by the variation of the active or reactive power.

III. UNIVERSAL MODEL OF GRID-CONNECTED CONVERTERS

This section will illustrate the universal model of grid-feeding converters, as an example, and it will stimulate the modelling of power converters with different control objectives. To illustrate this, certain assumptions are made:

- 1) As aforementioned, the inner AC current controller is almost the same for different control objectives. Furthermore, typically, the bandwidth of the current control loop is designed according to the switching frequency of the power electronic converter. The response of the current loop is generally in the millisecond range, and in contrast, the response time of outer control loops are commonly more than ten times slower [17]. Hence, the dynamics of the current control loops are neglected in this paper, and it is assumed that the AC currents can immediately follow the reference.
- 2) The universal model should reflect the relationship between the converter output power and internal voltage. The

Fig. 2. Diagram of the dual-loop control of grid-feeding converters.

fluctuation of the converter input power from the DC side, without considering the type of the DC source, is ignored, i.e., $\Delta P_{in} = 0$.

- 3) One of the advantages of VSCs is the capability to separately control the active power and reactive power [18]. Especially, in the DC-link voltage control timescale and when the connected AC grid is strong, the interaction from the active and reactive power can be ignored [11], which is adopted in the modelling.

With the abovementioned assumptions, grid-connected power converters can be modelled in the following in a universal way.

A. Voltage Phase Relationship in Converter Control System

The relationship of phases in the converter control system should be introduced first. Fig. 3 shows the voltage phases in steady state and after small disturbances, denoted in blue and red, respectively. In Fig. 3, θ_E^p is the difference between the internal voltage phase and PLL output voltage phase, θ_t^p is the difference between the terminal voltage phase and PLL output voltage phase, the subscript “0” denotes the initial value in steady state and the superscript “’” denotes the value after disturbances. As shown in Fig. 3, in steady state, the terminal voltage is typically aligned with the d -axis, which is determined by the PLL. When there is a disturbance, the tracking error of the terminal voltage phase will be introduced in the PLL, and then make the d -axis shift from the original voltage u_t , as marked by the red sector in Fig. 3. The deviation may consequently affect the stability of the power converter and the AC grid. Thus, the voltage phase relationship should be decisively considered in the modelling. It provides also information about the impact of the PLL on the system stability and thus, it enables the proper development of the controllers. Nonetheless, the voltage phase of the converter internal voltage can be derived from Fig. 3 as

$$\Delta\theta = (\theta_E^{p'} + \theta_t') - (\theta_{E0}^p + \theta_{t0}) = \Delta\theta_E^p + \Delta\theta_t \quad (1)$$

Fig. 3. Voltage phase relationship in the control system of power converters.

B. Input and Output of PLL

The PLL can be described by

$$\theta_p = [U_{tq}(k_{pPLL} + \frac{k_{iPLL}}{s}) + \omega_0] \frac{1}{s} \quad (2)$$

Linearizing (2) gets

$$\Delta\theta_p = U_{t0}\Delta\theta_t^p(k_{pPLL} + \frac{k_{iPLL}}{s}) \frac{1}{s} \quad (3)$$

Simplifying (3) with considering $U_{t0} \approx U_{g0} = 1$ yields

$$\Delta\theta_p = \frac{k_{iPLL} + k_{pPLL}s}{k_{iPLL} + k_{pPLL}s + s^2} \Delta\theta_t \quad (4)$$

Thus,

$$\begin{aligned} \Delta\theta_t^p &= \Delta\theta_t - \Delta\theta_p \\ &= \frac{s^2}{k_{iPLL} + k_{pPLL}s + s^2} \Delta\theta_t \end{aligned} \quad (5)$$

where k_{pPLL} and k_{iPLL} are the proportional and integral coefficients of the PI controller in the PLL.

C. Voltage Drop on The Output Filter

The voltage drop on the filter inductor can be given as

$$e = u_t + jX_f i \quad (6)$$

where X_f is the equivalent reactance of the filter inductor and i is the current flowing through the filter. Decomposing (6) in the dq -frame constructed by the PLL output voltage phase yields

$$E \cos \theta_E^p = U_t \cos \theta_t^p - X_f i_q \quad (7)$$

$$E \sin \theta_E^p = U_t \sin \theta_t^p + X_f i_d \quad (8)$$

Generally, in steady state, the voltage phase between E_0 and U_{t0} is small and the d -axis is coincident to the direction of U_{t0} [11], thus,

$$\theta_{E0}^p = \theta_0 - \theta_{p0} = \theta_0 - \theta_{t0} \approx 0 \quad (9)$$

Subsequently,

$$\begin{cases} \sin \theta_{E0}^P = \sin(\theta_0 - \theta_{p0}) \approx \theta_0 - \theta_{p0} \approx 0 \\ \cos \theta_{E0}^P = \cos(\theta_0 - \theta_{p0}) \approx 1 \end{cases} \quad (10)$$

Substituting (10) into (7) and (8), and linearizing them gives

$$\Delta E = \Delta U_t - X_f \Delta i_q \quad (11)$$

$$\Delta \theta_E^P = \frac{X_f}{E_0} \Delta i_d + \frac{U_{t0}}{E_0} \Delta \theta_t^P \quad (12)$$

D. Outer Control Loops

In this paper, the DC-link voltage controller is considered as the active power-correlated outer controller in order to indicate that the model can reflect the output power characteristics. On the other hand, for the reactive power-correlated outer controller, the reactive current reference is set to be zero for simplicity, as the active power and reactive power characteristics can be analyzed independently.

In order to reveal the converter output power characteristics, the deviation of the DC-link voltage should be transformed into the deviation of the active power. According to Fig. 2, the relationship between the DC-link voltage and the active power is given as

$$CU_{dc} \frac{dU_{dc}}{dt} = P_{in} - P \quad (13)$$

Linearizing (13) yields

$$\Delta U_{dc} = \frac{1}{sCU_{dc0}} (\Delta P_{in} - \Delta P) \quad (14)$$

As $\Delta P_{in} = 0$, then

$$\Delta U_{dc} = -\frac{1}{sCU_{dc0}} \Delta P \quad (15)$$

Furthermore, the AC current reference in the dq -frame can be obtained as

$$i_d^* = (U_{dc} - U_{dc}^*)(k_{pdc} + \frac{k_{idc}}{s}) \quad (16)$$

$$i_q^* = 0 \quad (17)$$

Considering that the AC currents follow the references immediately according to the assumption 1) in Section III, it gives

$$\Delta i_d = (k_{pdc} + \frac{k_{idc}}{s}) \Delta U_{dc} = -\frac{1}{sCU_{dc0}} (k_{pdc} + \frac{k_{idc}}{s}) \Delta P \quad (18)$$

$$\Delta i_q = 0 \quad (19)$$

where k_{pdc} and k_{idc} are the proportional and integral coefficients of the PI controller in the DC-link voltage control loop.

Substituting (18) into (12) and then substituting (4) into (1), the deviation of the internal voltage phase can be represented by the deviation of the active power ΔP and the terminal voltage phase $\Delta \theta_t$ as

$$\begin{aligned} \Delta \theta = & -\frac{X_f}{sCU_{dc0}E_0} (k_{pdc} + \frac{k_{idc}}{s}) \Delta P \\ & + \frac{E_0 k_{iPLL} + sE_0 k_{pPLL} + s^2 U_{t0}}{E_0 (k_{iPLL} + s k_{pPLL} + s^2)} \Delta \theta_t \end{aligned} \quad (20)$$

E. Power Exchange Between Internal and Terminal Voltage

The well-known power-angle equations of the synchronous generator are given as

$$\begin{cases} P = \frac{EU_t \sin(\theta - \theta_t)}{X_f} \\ Q = \frac{E^2 - EU_t \cos(\theta - \theta_t)}{X_f} \end{cases} \quad (21)$$

Substituting (10) into (21), after linearization, it yields

$$\Delta \theta = \Delta \theta_t + \frac{X_f}{E_0 U_{t0}} \Delta P \quad (22)$$

$$\Delta E = \frac{E_0}{2E_0 - U_{t0}} \Delta U_t + \frac{X_f}{2E_0 - U_{t0}} \Delta Q \quad (23)$$

which can be further simplified. Then, the model of the power converter reflecting the relationship between the active power and internal voltage phase can be obtained as

$$\Delta \theta = G_{p\theta} \Delta P = K_0 + \frac{K_1}{s} + \frac{K_2}{s^2} + \frac{K_3}{s^3} + \frac{K_4}{s^4} \quad (24)$$

where

$$\begin{aligned} K_0 &= -\frac{X_f}{E_0 (U_{t0} - E_0)} \\ K_1 &= -\frac{X_f (CU_{dc0} k_{pPLL} + U_{t0} k_{pdc})}{CU_{dc0} U_{t0} (U_{t0} - E_0)} \\ K_2 &= -\frac{X_f (U_{t0} (k_{pdc} k_{pPLL} + k_{idc}) + CU_{dc0} k_{iPLL})}{CU_{dc0} U_{t0} (U_{t0} - E_0)} \\ K_3 &= -\frac{X_f (k_{idc} k_{pPLL} + k_{pdc} k_{iPLL})}{CU_{dc0} (U_{t0} - E_0)} \\ K_4 &= -\frac{X_f k_{idc} k_{iPLL}}{CU_{dc0} (U_{t0} - E_0)} \end{aligned}$$

As shown in (24), different from the virtual synchronous generator (VSG), the virtual inertia characteristic of dual-loop controlled grid-connected converter is in the s -domain as a transfer function. It facilitates the active power-frequency stability analysis of large-scale power systems. Meanwhile, the model can be easily reformulated into the form like the swing equation of synchronous generator [11], which can directly provide more information about the virtual inertia.

The impact of the active power deviation on the stability of the PLL output is important as well. The small-signal relationship between the active power and internal voltage phase can be obtained from (4) as

$$\begin{aligned}\Delta\theta_p &= G_{p\theta_p} \Delta P \\ &= -\frac{Xf(U_{i0}(sk_{pdc} + k_{idc}) + s^2 CU_{dc0})(sk_{pPLL} + k_{iPLL})}{s^4 CU_{dc0} U_{i0}(U_{i0} - E_0)} \Delta P\end{aligned}\quad (25)$$

The reactive current reference is set to be zero for simplicity, which makes the reactive power-internal voltage magnitude relationship to be linear in the DC-link voltage control timescale, and it is not discussed in this paper. However, with advanced reactive power control strategies, the reactive power-internal voltage magnitude relationship can also be obtained as

$$\Delta E = G_{QE} \Delta Q \quad (26)$$

The internal voltage of the power converter will follow the power distribution of the AC grid. It in turn will affect the converter internal voltage. The feedback loop from the power to the converter internal voltage is related to the topology and impedance distribution of the grid, but it is not difficult to build the model of the grid, as it has been investigated in [13]. In the model shown in Fig. 1, for example, the power exchange between the internal voltage and AC grid infinite-bus voltage is given as

$$\begin{cases} P = \frac{EU_g \sin \theta}{X_f + X_g} \\ Q = \frac{E^2 - EU_g \cos \theta}{X_f + X_g} \end{cases} \quad (27)$$

which can be linearized without considering the coupling of the active power and reactive power as

$$\Delta P = K_{\theta P} \Delta \theta = \frac{E_0 U_{g0} \cos \theta_0}{X_f + X_g} \Delta \theta \quad (28)$$

$$\Delta Q = K_{EQ} \Delta E = \frac{2E_0 - U_{g0} \cos \theta_0}{X_f + X_g} \Delta E \quad (29)$$

From the above, the universal model of grid-connected converters reflecting external characteristics can be built up as shown in Fig. 4, where the input of the reactive power-internal voltage amplitude loop is also zero, as there is no reactive power in DC systems. In the proposed model, the transfer functions are all determined by the parameters of the power converters. It maintains the effectiveness to evaluate the impact of system parameters, especially the power converter controller parameters, on the system stability.

IV. CASE STUDY

To validate the proposed model, a case study is presented in this section. A power electronic converter connected to an infinite-bus as shown in Fig. 1 is simulated, of which the parameters are shown in Table I, where k_{pi} and k_{ii} are the proportional and integral coefficients of the PI controller in the current control loop. The PI control coefficients are selected by experience in this paper and can be determined by solving optimization problems based on the proposed model. Accordingly, the transfer functions $G_{P\theta}$, $G_{P\theta_p}$, and $K_{\theta P}$ can be obtained. Three sets of proportional coefficients of the PI controller for the PLL are compared, and the system dynamics are analyzed.

Fig. 4. Diagram of the universal model for grid-connected converters.

TABLE I. SYSTEM PARAMETERS FOR MODEL ANALYSIS.

Descriptions	Values
Rated power	20 kW
Rated DC voltage	780 V
Rated AC voltage	400 V
DC-link capacitor	10 mF
Converter inductance	2.53 mH
Equivalent grid inductance	2.53 mH
Fundamental frequency	50 Hz
(k_{pdc}, k_{idc})	(0.5, 50)
(k_{pi}, k_{ii})	(0.5, 50)
(k_{pPLL}, k_{iPLL})	(10, 100)

A. Impact of Active Power on The Internal Voltage Phase Stability

By increasing k_{pPLL} from 1 to 100, the closed-loop eigenvalue distribution of the P_{in} - θ loop is obtained, as shown in Fig. 5. It is clearly demonstrated in Fig. 5 that when k_{pPLL} increases, the eigenvalues of the closed-loop system from the active power to the internal voltage phase will move to the left, which means that the system becomes more stable. Then, when $k_{pPLL} = 1, 10$, and 100, the open-loop Bode diagrams of the transfer function from the input active power to internal voltage phase $-G_{P\theta}$ are obtained, as shown in Fig. 6. It can be observed in Fig. 6 that when k_{pPLL} becomes larger, the gain margin of the system will be larger, meaning that the system will be more stable.

B. Impact of Active Power on The PLL Output Stability

As discussed in Section III, the stability of the PLL is important as well. If the tracking error of the PLL exceeds the limitation, the synchronization of the power converter will be seriously affected, and the converter may even be required to be disconnected from the grid, which is not preferred in operation. When $k_{pPLL} = 1, 10$, and 100, the open-loop Bode

Fig. 5. Closed-loop eigenvalues of the active power-internal voltage phase loop with increasing k_{pPLL} for the VSC.

Fig. 6. Bode diagram of $-G_{p\theta}$ when $k_{pPLL} = 1, 10$, and 100 .

Fig. 7. Bode diagram of $-G_{p\theta p}$ when $k_{pPLL} = 1, 10$, and 100 .

Fig. 8. Responses of the DC-link voltage, converter output active power, and PLL output frequency when the phase of U_g increases 10° at $t = 3$ s with $k_{pPLL} = 1, 10$, and 100 .

diagrams of the transfer function from the input active power to the PLL output phase $-G_{p\theta p}$ can be obtained as shown in Fig. 7. When k_{pPLL} becomes larger, the gain margin of $G_{p\theta p}$ will become smaller, which indicates that the PLL will be less stable. According to the Bode diagram analysis of $-G_{p\theta}$ and $-G_{p\theta p}$, it can be concluded that the impacts of the power converter output active power on the stability of internal voltage phase and on the PLL output frequency are opposite. The discovery is important to the design of the converter controller.

C. Simulation Results

To validate the above analysis, a test system as shown in Fig. 1 is simulated in PSCAD/EMTDC. The parameters of the system are given in Table I. At $t = 2$ s, a disturbance is imposed, where the phase of the AC grid infinite-bus voltage increases by 10° , and the responses of the system with different PLL gains k_{pPLL} are given in Fig. 8. It can be observed in Fig. 8 that when the system is disturbed, oscillations will appear. The

controller parameters have a great impact on system dynamics under disturbances. As shown in Fig. 8, when k_{pPLL} increases, the oscillations of the DC-link voltage and converter output active power become smaller. It means that the active power-internal voltage phase characteristics of the power converters are more stable, which guarantees the power angle and frequency stability of the system. On the other hand, with k_{pPLL} increasing from 1 to 100, the oscillation of the PLL output frequency becomes more serious. It means that a larger k_{pPLL} leads on more unstable operation of the PLL. In all, the simulation results have validated the previous analysis based on the proposed model. The effectiveness of the model has been confirmed.

V. CONCLUSIONS

A universal model for grid-connected converters reflecting the output power-internal voltage characteristics was proposed in this paper. Firstly, the power converters with different control strategies were introduced and the need of a universal model was demonstrated. Referring to the swing equation of the synchronous generators, the converter was modelled as a transfer function from the power to the internal voltage, which can be divided into the active power-internal voltage phase loop and reactive power-internal voltage amplitude. Likewise, the transfer function from the active power to the PLL output frequency was presented in the model to evaluate the performance of the PLL. A case study has been performed to validate the model. The simulation results revealed that the proposed model was relatively accurate in the stability analysis of power converters, and it can support the control system design.

In the future, the model will be improved to provide sufficient information, especially those related to the AC grid stability, while maintaining its simplicity. For instance, the impact of the AC grid stiffness on the power-internal voltage characteristics of converters will be considered, which is of importance to analyze power system stability issues. More importantly, the model will be aggregated to the application of power electronic-based power systems.

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