

Power Quality Improvements in Wind Based DG Systems using Solid State Transformer

Subhadeep Paladhi¹ and Ashok S.²

Abstract— Along with the random increment of power demand throughout the world, the amount of renewable energy integration into the conventional grid is also increasing day by day. Wind power is being found as one of the most rapidly increasing renewable energy resources in the present scenario. As a result of the wind power being an uncontrollable resource, various problems regarding power quality, power system stability, reactive power consumption and protection issues arise. Though the Solid State Transformer (SST) has been found to be useful in integration of different distributed energy resources in the distribution grid with multiple functionalities, research gaps are still found in SST application in case of wind power integration. In this paper, the SST based mitigation of some power quality issues like voltage sag and swell at point of common coupling (PCC), reactive power consumption, power factor improvement etc. which exist in the wind based DG systems are presented through PSCAD/EMTDC simulation using suitable case study.

Index Terms— Solid State Transformer, Power Quality, Voltage Sag and Voltage swell, Reactive Power Compensation, Power factor Improvement.

1 INTRODUCTION

WITH the increment of power demand throughout the world, the penetration of renewable energy is increasing day by day, where the wind energy has risen as a perfect solution thus far. For being an uncontrollable resource, it becomes a great challenge to integrate large wind farms into the distribution grid as per the power quality, power system stability and protection point of view. Additionally, the step up power transformers are used to boost the voltage level needed for interconnecting wind power to the distribution grid which creates transportation problem because of its bulky size. Placement optimization is another great problem for the reactive power compensators (like STATCOM, capacitor banks etc.) used for improving the power quality issues like voltage level improvement and power factor improvement [1], [2].

Solid State Transformer (SST) is being considered as one of the most current research interests for integration of distributed energy resources (DERs). For the unavailability of high voltage and power level power electronic devices, the research regarding SST was stopped at its early stage of research. With the development of high voltage and high power level power electronic devices, researches have been started again for the application of SST in high power level applications. The research approaches regarding SST are divided mainly into two directions. One is the topology and architecture development in order to reduce the power level of the SST component and the other direction is to find the suitability of SST in different applications [4]. SST is already found useful in the several applications such as traction/locomotives, distributed source integration (like solar farm, wind power), charge station, and smart grid application in order to reduce the volume and

weight of the system and improve the power quality and protection issues where conventional low frequency transformers are already dominating [1], [6].

The reactive power compensation, active power control and voltage conversion properties are already verified in wind power integrated grid using SST [1]. Some fault isolation algorithms are proposed and verified for distribution grid using SST with PV and fuel cell as the distributed energy resources (DER) [9], [10], [11], [12]. Though the suitability of SST application in wind based DG systems are already verified, some important approaches like voltage level and power factor improvement at the Point of Common Coupling (PCC) in case of dynamic load condition without using any Static Compensators (like STATCOM) have not been verified still now.

In this paper the voltage sag and swell mitigation, power factor improvement at PCC without using any static compensators in a SST interfaced wind based DG system are verified along with the active and reactive power control capabilities through PSCAD/EMTDC simulation using suitable case study. Section 2 describes the overview of the SST architectures and topologies, conventional and SST interfaced wind power integration techniques and power quality issues present in a wind based DG system. The modeling of SST with controllers designing approach is presented in Section 3. In Section 4, a system case study based on the data of Kanjikode wind farm is described. The simulation results are shown in Section 5 to show the advantages of SST based technique over conventional.

2 OVERVIEW OF SOLID STATE TRANSFORMER (SST), WIND POWER INTEGRATION TECHNIQUES AND POWER QUALITY ISSUES

2.1 Solid State Transformer (SST)

The SST is typically composed of a high-voltage ac/dc converter regulating a high-voltage dc bus (ac voltage during reactive power compensation), an isolated high-frequency operated dual active bridge dc/dc converter regulating the sec-

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ondary dc bus, and a dc/ac converter regulating the output of the terminal ac voltage. The functional diagram of SST has been shown in Figure 1.

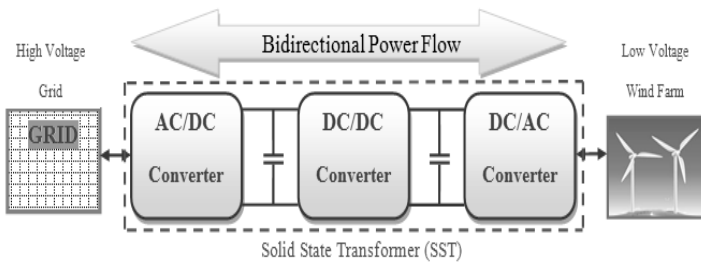


Fig.1. Structural Overview of SST

SST was first mentioned in the research in 1980 by James Brooks [8]. But due to the limitation of higher voltage and power level power semiconductor devices, SST was not found as a practical solution at that time. With the advancement of semiconductor technology many organizations are trying to make the high power SST. The researchers at ETH Zurich are working with matrix converter based SST topology with the code name as MAGACube [7]. The FREEDM project is investigating a SST based on a single phase system with different modularity [1], [9], [11], [12]. Four important topologies by ABB, GE, UNIFLEX and EPRI are described in [6].

15 kV SiC MOSFET has been found to be useful than IGBT devices for making high power SST [6]. Different amorphous alloys, nanocrystalline core, METAGLASS core has been found to be useful for high frequency transformer core with maximum flux density [6]. By increasing the number of H bridges in converter stage (in proper combination of series and parallel connection) the problem regarding high voltage and power level can be solved [6], [7].

Conventional low frequency power transformers have been greatly challenged by solid-state transformer technologies. Simply, the main function of conventional transformer is input-output voltage and current transformation. So the disturbances on one side are fully reflected on the opposite side. SST has been found to be a promising device to overcome this issue [1], [4], [6]. Potential advantages of SST over conventional low frequency transformers are low volume and weight (due to its high-frequency operation compared with 50-Hz transformer), fault isolation, voltage regulation, insusceptible to harmonics, easy integration of renewable energy resources and energy storage, etc. [1], [4], [5], [6], [7], [8], [9], [10], [11], [12].

2.2 Conventional Wind Power Integrated Grid

Among the various techniques used for the conversion of wind energy into electric energy, induction generator based technology is the most popular and widely used technique. Three mainly used Wind Farm architectures are SCIG based wind energy system, doubly fed induction generator (DFIG)-based wind energy system, and directly driven synchronous generator (DDSG)-based wind energy system, shown in Figure 2. SCIG is considered as the most economical solution because of the direct coupling with the grid as shown in Figure 2(a). Thyristor controlled capacitor bank is generally used for power factor correction compensating local reactive power to

cope up with the wind power generation variation. The wind generation using DFIG and DDSG employs back-to-back converters using the power partially and fully to decouple the mechanical and electrical rotor frequencies as described in Figure 2(b) and Figure 2(c).

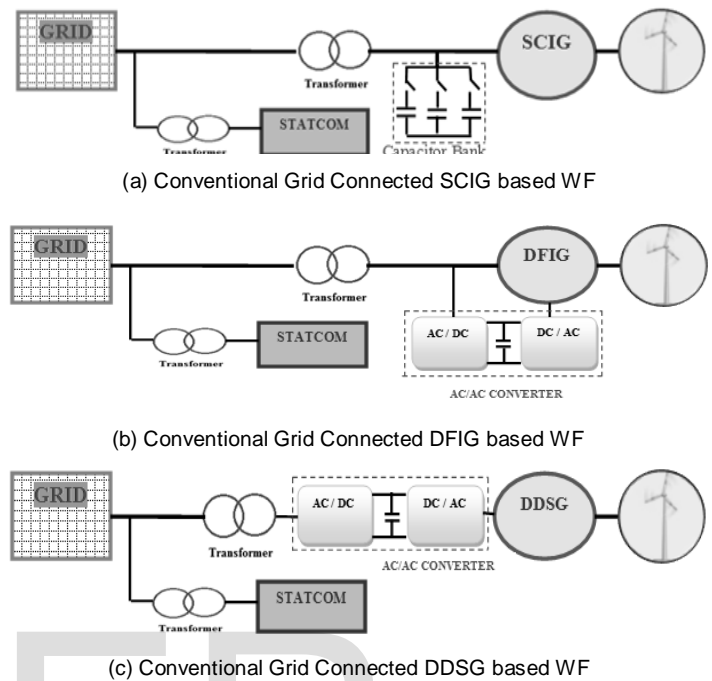


Fig.2. Overview of Conventional Grid connected WFs

2.3 SST interfaced Wind Farms

Wind energy systems connected to distribution grid through SST are shown in Figure 3. It eliminates capacitor bank, two transformers and one STATCOM for SCIG based wind farm (WF), two transformers and one STATCOM for DFIG based WF and back to back converter, two transformers and one STATCOM for DDSG based WF [1]. This describes the structural advantages of SSTs in interfacing wind power with the grid.

2.4 Power Quality and Stability Issues Present in Wind Based DG Systems

As for being uncontrollable resource, wind power integrated distributed grid faces different problems like voltage stability problems, poor power factor issues etc. One main problem with induction generator based wind farm is the reactive power consumption issue. So thyristor controlled capacitor banks are needed to compensate local reactive power consumption. With dynamic load condition at PCC creates voltage fluctuations (like sag and swell), which creates rotor angle stability problem in wind generators. Sometimes because of low voltage condition at PCC, wind farms are needed to disconnect from the grid. This all problems come under power quality and stability issues.

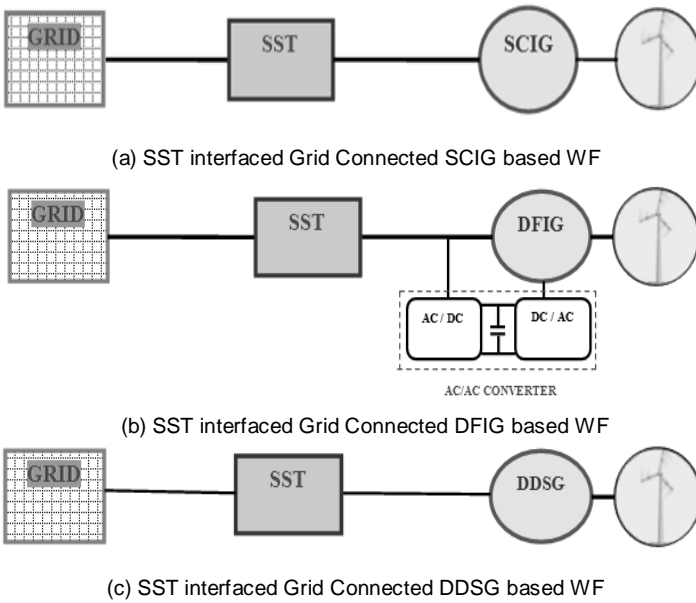


Fig.3. Overview of SST based Grid connected WFs

3 MODELING OF SST AND CONTROLLER DESIGNING LOGIC

Among the different SST topologies, the simple cascaded three phase switching model of SST is used in this paper for wind power interfacing. AC voltages are controlled for reactive power compensation and the dc voltages are controlled for active power control [1]. Fig. 4 shows a cascaded-type three-phase SST. Physical limitations for power devices and magnetic materials are neglected during modeling and simulation. First stage of SST is a three-phase bidirectional ac/dc pulse width modulation (PWM) converter. The dc/dc stage of SST is consisted of a dual active bridge (DAB) or dual half bridge (DHB) converter representing the most attractive candidate for high-power applications requiring isolation, as it can perform zero-voltage switching in a wide operation range [1].

In the aforementioned SST configuration, V_{PCC} is the PCC voltage, i_g is the PCC current flowing through the SST, V_{hdc} is the high dc bus voltage, V_{ldc} is the low dc bus voltage, V_{wind} is the wind farm side SST terminal voltage, and i_{wind} is the current through SST terminal at wind farm side.

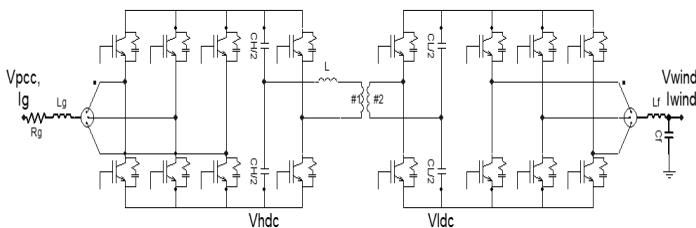


Fig.4. Switching model of Three Phase SST

3.1 Modeling of Rectifier Stage

The basic differential equations of the rectifier stage are:

$$\frac{d\vec{i}_g}{dt} = \frac{3E_H}{L_g} \vec{d}_h - \frac{\vec{v}_{pcc}}{L_g} - \frac{R_g}{L_g} \vec{i}_g \quad (1)$$

$$\frac{dE_H}{dt} = -\frac{E_H}{R_g C_H} - \frac{\vec{d}_h^T \vec{i}_g}{2C_H} \quad (2)$$

Where,

$$\vec{i}_g = \begin{bmatrix} i_{ga} \\ i_{gb} \\ i_{gc} \end{bmatrix}, \vec{d}_h = \begin{bmatrix} d_{ha} \\ d_{hb} \\ d_{hc} \end{bmatrix}, \vec{v}_{pcc} = \begin{bmatrix} v_{pcca} \\ v_{pccb} \\ v_{pccc} \end{bmatrix}$$

i_{ga} ; i_{gb} ; i_{gc} are the grid side current, v_{pcca} ; v_{pccb} ; v_{pccc} are the grid side voltage, R_g is the grid side line resistance, L_g is the grid side inductor, E_H the high voltage DC bus voltage, C_H is the high voltage DC capacitor, d_{ha} ; d_{hb} ; d_{hc} are the rectifier PWM duty cycle for the three phases respectively.

The equation 1 and 2 are transformed into d-q coordinate using the following equation

$$[A_{dq}] = [T].[A_{abc}] \quad (3)$$

Where,

$$[T] = \begin{bmatrix} \sin \gamma & -\cos \gamma \\ \cos \gamma & \sin \gamma \end{bmatrix}; \gamma = 2\pi f_N t; f_N \text{ is the rated frequency.}$$

The derived differential equations in d-q coordinates are as follows:

$$\frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{3E_H}{L_g} \begin{bmatrix} d_d \\ d_q \end{bmatrix} - \frac{1}{L_g} \begin{bmatrix} v_{pccd} \\ v_{pccq} \end{bmatrix} - \begin{bmatrix} \frac{R_g}{L_g} & -\omega \\ \omega & \frac{R_g}{L_g} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (4)$$

$$\frac{dE_H}{dt} = -\frac{E_H}{R_g C_H} - \frac{\vec{d}_h^T \vec{i}_g}{2C_H} \quad (5)$$

Using these equations the controllers are modeled. The detailed controller logic for rectifier stage using d-q vector control is shown in Fig. 5(a).

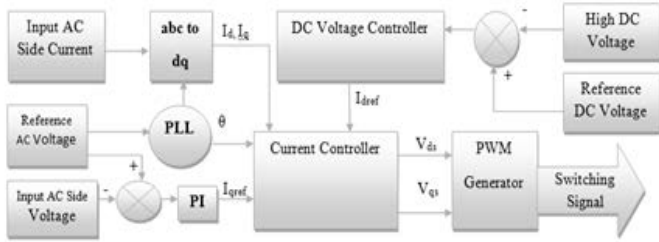
As the SST is used for bidirectional power flow, this stage is used as rectifier for transferring power from grid to secondary side. But in this paper the power is transferring from wind farm to distribution grid. So the described approach has been used to design the wind farm side converter stage.

3.2 Modeling of Dual Active Bridge (DAB) Converter Stage

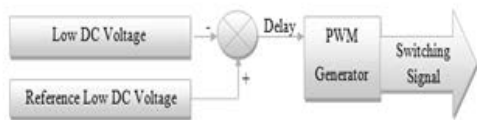
The dual active bridge consists of a high voltage inverter, a high frequency transformer and a low voltage rectifier. The DAB converter controls the low voltage dc link voltage. Zero voltage switching for all the switches, relatively low voltage stress for the switches, low passive component ratings and complete symmetry of configuration are the advantages of DAB topology that allows seamless control for bidirectional power flow. Real power flows through the DAB converter is

given by the equation 6.

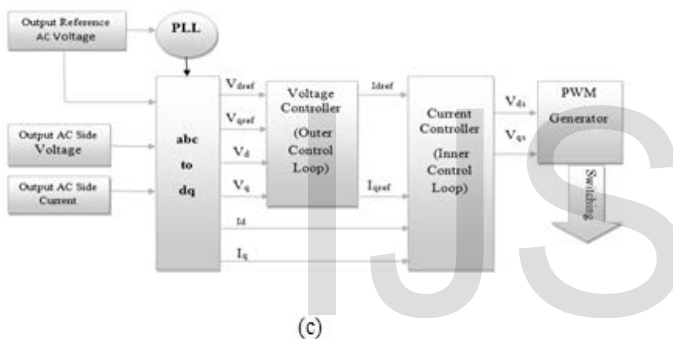
$$P_{DHB} = \frac{E_H E_L}{2L f_s} \Phi(1 - \Phi) \tag{6}$$



(a)



(b)



(c)

Fig. 5: SST Controller logic for (a) High Voltage Rectifier Stage, (b) Dual Active Bridge Stage, (c) Low voltage inverter Stage

where, E_H is input side high voltage DC voltage, f_s is switching frequency, L is leakage inductance, E_L is output side low voltage DC link voltage referred to input side and is ratio of time delay between the two bridges to one half of switching period.

A phase regulation scheme is used in the DAB controller adjusting the phase shift between high and low-side converters using simple PI controller to control the power flow as shown in Fig. 5(b).

In this paper this similar control technique has been used for DAB to control the HVDC bus voltage as the power flows from wind farm to grid.

3.3 Modeling of Low Voltage Inverter Stage

A dual loop strategy in dq coordinate is used for the inverter stage. Cascaded inductor current loop is used as the inner loop for fast dynamic responding. This controller is modified according to the variation of different wind generators. The controller logic for low voltage inverter stage is shown in Fig. 5(c).

In this paper this control logic has been used for first stage i.e. grid side converter stage to flow the power from wind farm to grid and this stage is designed with the control logic

explained in rectifier stage.

4 CASE STUDY

A system case study is carried out with the layout and practical data from Kanjikode 2MW SCIG based wind farm, situated in Kerala, India. The wind farm has nine units of Vestas V27 225kW wind turbine and SCIG is used as wind generator with a rated output of 225kW, 400V, 50Hz. The nine units are connected to the three 1MVA, 415V/22kV, 50 Hz step up transformer divided into three units for each. This is connected to 110kV and the 220kV grid using 25MVA, 22kV/110kV, 50Hz distribution transformer and 160MVA, 110kV/220kV, 50Hz autotransformer respectively. Thyristor controlled 100kVAR capacitor bank is connected with each unit for power factor improvement.

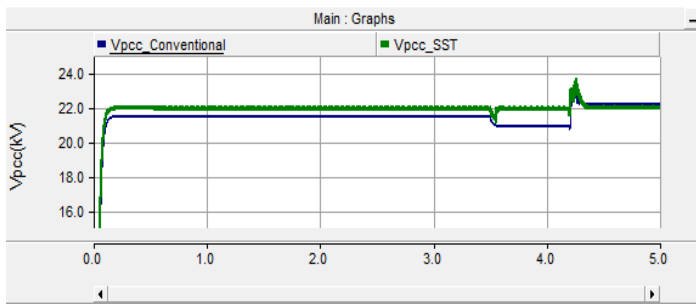
For the simplicity of simulation for the SST interfaced wind farm the all nine units are connected to one 3MVA SST i.e. same as three 1MVA step up transformer unit. The simulation parameters of 3MVA SST are pre-sented in Table 1.

TABLE 1
SIMULATION PARAMETERS FOR SST USED IN CASE STUDY

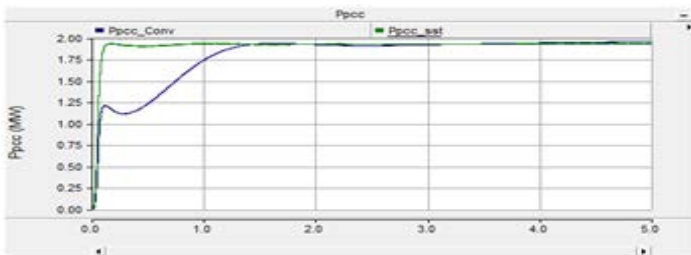
| | |
|------------------------------|--------------|
| HVDC Capacitor Value | 10μF |
| LVDC Capacitor value | 50mF |
| HVDC Bus Voltage | 32kV |
| LVDC Bus Voltage | 600V |
| Switching Frequency | |
| • Rectifier Stage | 3kHz |
| • DAB Stage | 3.6kHz |
| • Inverter Stage | 1.2 kHz |
| Transformer Parameters | |
| • Turns Ratio | 27 : 1 |
| • Leakage Inductance | 18mH |
| • Transformer Frequency | 2kHz |
| Filter Parameters | |
| • Line Inductance | 675μH |
| • LC Filter at Inverter side | 240mH, 160μF |

Fig. 6(a) shows the Kanjikode wind farm layout i.e. the SCIG based 2.025 MW wind farm is first connected to 22kV PCC and then 110kV bus and 220kV through step up transformers of above mentioned rating and capacitor bank is connected to each wind farm unit of the rating mentioned before. Fig. 6(b) shows the same wind farm connected to 22kV PCC through 3MVA (same as step up transformer rating) Solid State Transformer (SST) and then to 110kV bus and 220kV grid in the same way as conventional. But here no capacitor bank is used.

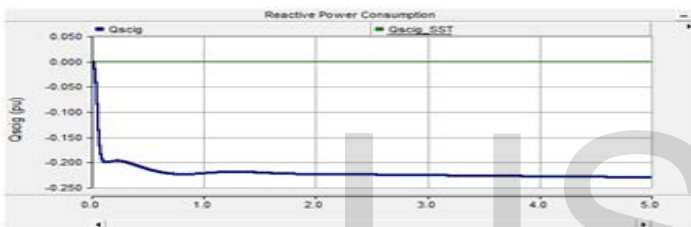
To verify the voltage sag and swell condition under dynamic load condition, three different loads are been applied at different timing for a definite short period. L_1 (1MW+0.2MVAR/ph) for 0 to 3.5s. L_2 (3MW+1MVAR/ph) for 3.5s to 4.2s and L_3 (0.01MW-1MVAR/ph) for 4.2s to 5s.



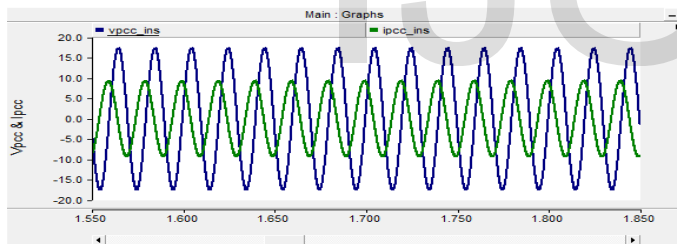
(a) PCC Voltage at Dynamic Load Condition



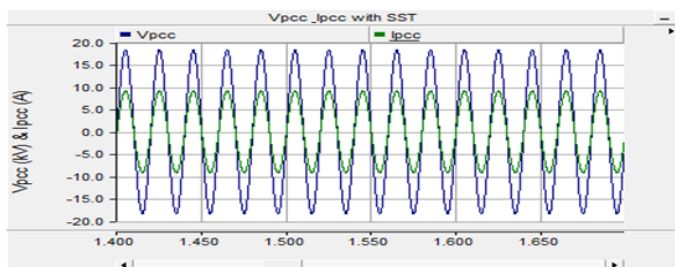
(b) Active Power Transfer by SST from Wind Farm with L_1 at PCC



(c) Reactive Power Consumption from Grid by SCIG based WF



(d) Voltage and Current Waveform at PCC without SST with L_1 at PCC



(e) Voltage and Current Waveform at PCC with SST with L_1 at PCC

Fig.7. Simulation Results from Case Study

6 CONCLUSION

The effectiveness of Solid State Transformer in voltage sag and voltage swell mitigation, reactive power compensation and power factor improvement in wind power integration has

been presented in this paper. The constructional advantages and active and reactive power control capability are also verified through case study using PSCAD/EMTDC simulation tool.

Among the three types of wind generators, the SCIG-driven wind farm consumes more reactive power compare to the others. For that reason more reactive power compensation is required. So the conclusion drawn from this case study can also be applied to the WFs driven by DFIG and DDSG since the control logics are same for all these systems.

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