

PSCAD/EMTDC based Modeling and Analysis of Power Quality of Variable Speed Wind Turbine with STATCOM or SVC

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Abstract: This paper presents dynamic modeling and simulation of a grid connected variable speed wind turbine (VSWT) using PSCAD/EMTDC, a widely used power system transient analysis tool. The purpose of this paper is analysis of the power quality of VSWT with STATCOM and/or SVC using PSCAD/EMTDC. Grid-connected wind turbines have variable output power and voltage due to the variable nature of wind and aerodynamic phenomena. However, presence of STATCOM and SVC can improve voltage delivered to the grid. In this paper a model of VSWT is studied with three-phase fault at the PCC bus with SVC and STATCOM. The obtained results demonstrate an improvement on voltage and power with adding STATCOM and/or SVC. However, STATCOM has more favorable effect than SVC on the improvement of wind turbine output voltage and damping three phase fault oscillations. All modelings and simulations are presented by PSCAD/ EMTDC.

Keywords: STATCOM, SVC, Power Quality, Variable Speed Wind Turbine.

I. Introduction

To have sustainable growth and social progress, it is necessary to meet the energy needed by utilizing the renewable energy resources like wind, biomass, hydro, co-generation, etc. In sustainable energy system, energy conservation and using of renewable resources are the key paradigm. The need to integrate the renewable energy like wind energy into power system is to make it possible to minimize the environmental impact on conventional plant [1]. The operation of the variable speed turbine than fixed speed turbine can reduce fluctuations and improve the supply of reactive power. The variable speed turbine technology is growing faster due to low price of power electronic device [1]. The output voltage and power of wind turbine may change or fluctuate due to aerodynamic phenomena, such as yaw, wake and mechanical vibrations. In this regard, some of the quality criteria and constraints (such as Flicker) introduce important limitations in the use of wind turbines and their connection to the distribution grid. Especially when the grid is a poor grid and a considerable amount of supplies are produced by wind turbine [2]. A way to reduce changing voltage and power quality of the grid is using of STATCOM and/or SVC in grid.

The power quality is an essential customer focused measure and is greatly affected by the operation of a distribution and transmission network. The issue of power quality is of great importance to the wind turbine [2]. There has been an extensive growth and quick development in the exploitation of wind energy in recent years. The individual units can be of large capacity up to 2 MW, feeding into distribution network, particularly with customers connected in close proximity [6]. Today, more than 28 000 wind generating turbines are successfully operating all over the world. In the fixed speed wind turbine operation, all the fluctuation in the wind speed are transmitted as fluctuations in the mechanical torque and electrical power on the grid and leads to large voltage fluctuations. During the normal operation, wind turbine produces a continuous variable output power. These power variations are mainly caused by the effect of turbulence, wind shear, tower-shadow and control system in the power system. Thus, the network needs to manage for such fluctuations. The power quality issues can be viewed with respect to the wind generation, transmission and distribution network, such as voltage sag, swells, flickers, harmonics etc.

Reference [2] presents dynamic modeling and simulation of a grid connected variable speed wind turbine (VSWT) with simple current control scheme for voltage source inverter (VSI) in PSCAD. A control strategy implemented for a successful operation of a micro grid using MATLAB and PSCAD software is reported [3]. Strategies with double control loops were proposed in [4] and [5] for the self-excited induction SEIG-VSI system using MATLAB. The purpose of this paper is to modeling and analysis of variable speed wind turbine based on PSCAD/EMTDC with the presence of SVC and/or STATCOM to improve stability of the power quality. Also in this paper, voltage oriented control (VOC) with decoupled controller is used to control of the inverter. With this strategy a current-controlled VSI can transfer the desired active and reactive power by generating an AC current with a desired reference waveform.

The paper is organized as follows; Section II describes the system modeling to study. Then, the simulated results on performance of modeling is described in Section III. Conclusions drawn from the study are presented in Section IV.

II. System Modeling to Study

A. Wind Model

Fig.1 shows a wind turbine connected to a grid for power quality study with FACTS devices. The variable speed wind turbine, which uses an ac/dc/ac converter with a dc link, is connected to load and grid at PCC bus. Also FACTS devices are connected to the PCC bus. Wind turbine model includes the wind model, turbine model and the synchronous machine model.

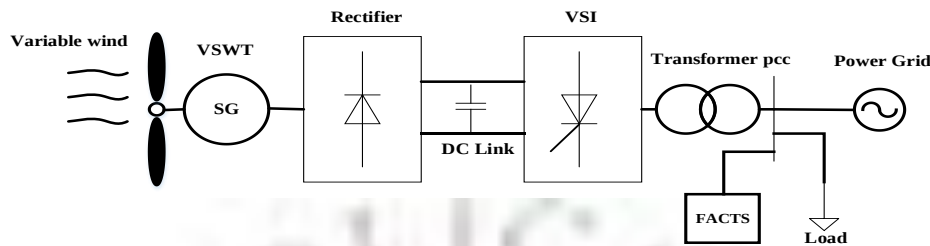


Figure 1. Schematic of a wind turbine

The wind model selected for this study is a four component model [3], and can be described by (1).

$$V_{wind} = V_{base} + V_{gust} + V_{ramp} + V_{noise} \quad (1)$$

Where

V_{base} is the base wind speed [m/s]

V_{gust} is the gust wind component [m/s]

V_{ramp} is the ramp wind component [m/s]

V_{noise} is the noise wind component [m/s]

The base component is a constant speed, while the gust component can be usually expressed as a sine or cosine wave function [7]. In this simulation, a combination of different cosine functions is used for the gust wind. The ramp wind component can be represented by the built-in ramp function model of the program. The noise component of the wind speed is defined in this study by a triangle wave function, of which the frequency and magnitude are adjustable. Since there is a triangle wave generator available in the commercial version of the software, it is used as a noise generator. Based on the stated four components, a wind speed model is constructed by integrating the built in functions and logic circuits provided in the program.

B. Wind Turbine

Table 1 shows technical features of the proposed wind turbine. This wind turbine can be modeled using equations (2)-(4).

Table1. Parameters for wind turbine.

Turbine quantity	Value
Rating	1[MW]
Blade radius	37.38[m]
Air density	0.55[kg/m ³]
Rated speed	2.808[rad/s]
Rated wind speed	12.35[m/s]
Cut-in speed	4[m/s]
Cut-out speed	25[m/s]
Blade pitch angle	0[degree]
Rated mechanical speed	26.814[rpm]
MVA_{base}	1[MVA]
f_{base}	18.77[Hz]
Inertia constant of turbine	0.7553[s]
Inertia constant of generator	0.3925[s]
Shaft spring constant	4200[N.m/rad]

$$\lambda = \frac{\omega_m R}{V_{wind}} \quad (2)$$

$$P_m = 0.5 \rho \pi R^2 C_p V_{wind}^3 \quad (3)$$

$$T_m = \frac{P_m}{\omega_m} \quad (4)$$

Where:

λ is tip speed ratio

ω_m is blade angular speed [mechanical rad/s]

R is blade radius [m]

V_{wind} is wind speed [m/s]

P_m is mechanical power from wind blades [kW]

ρ is air density [kg/m³]

C_p is power coefficient

T_m is mechanical torque from wind blades [N·m]

The mechanical torque obtained from (4) will act as the input torque to the synchronous generator to drive it. C_p may be expressed as a function of the tip speed ratio λ as follows [8]:

$$C_p = (0.44 - 0.0167) \sin \frac{\pi(\lambda - 2)}{(13 - 0.3)\beta} - 0.00184(\lambda - 2)\pi \quad (5)$$

Where β is the blade pitch angle. For a fixed pitch turbine the value of β is set to a constant value.

C. Synchronouse Machine

The PSCAD/EMTP provides a fully developed synchronous machine model, which is based on generalized machine theory [10]. Using this model both sub-transient and transient behavior of the machine can be examined. It is considered that the synchronous generator is equipped with an exciter identical to IEEE type 1 model [9]. The exciter plays a role of meeting the dc link voltage requirement, as may be described by (6), for the three-phase voltage source inverter to create voltage waveforms with a nominal value of magnitude.

$$V_{dc} = \frac{2\sqrt{2}V_{ac_rms}}{D_{max}} \quad (6)$$

Where

V_{dc} is dc link voltage of power electronics

V_{ac_rms} is RMS value of the AC line to ground voltage of the inverter

D_{max} is maximum duty cycle

In gearless type variable speed operation, electrical speed of the wind generator is not consistent with the synchronous speed of the electric network and generally it is much slower than the synchronous speed. The electrical base frequency of the machine must be set equal to the rated speed of the wind turbine. The base angular frequency ω_B may be obtained from (7) and (8). Basic parameters used for the direct-drive generator model are given in Table 2. Many other input parameters regarding inherent characteristics of a machine, e. g. damping, leakage and saturation have been left to default values provided in PSCAD/EMTP [7].

$$f_B = \frac{N_P}{2} \frac{rpm_{tur}}{60} \quad (7)$$

$$\omega_B = 2\pi f_B = \pi \cdot N_P \cdot \frac{rpm_{tur}}{60} \quad (8)$$

Table 2. Basic data for the direct-drive Generator

Generator quantity	Value
Rated Power	1.2[MW]
Rated Voltage (line-to-natural)	1.1[KV]
Rated Line Current	0.6364[kA]
Number of poles	84
Base angular frequency	117.93[rad/s]

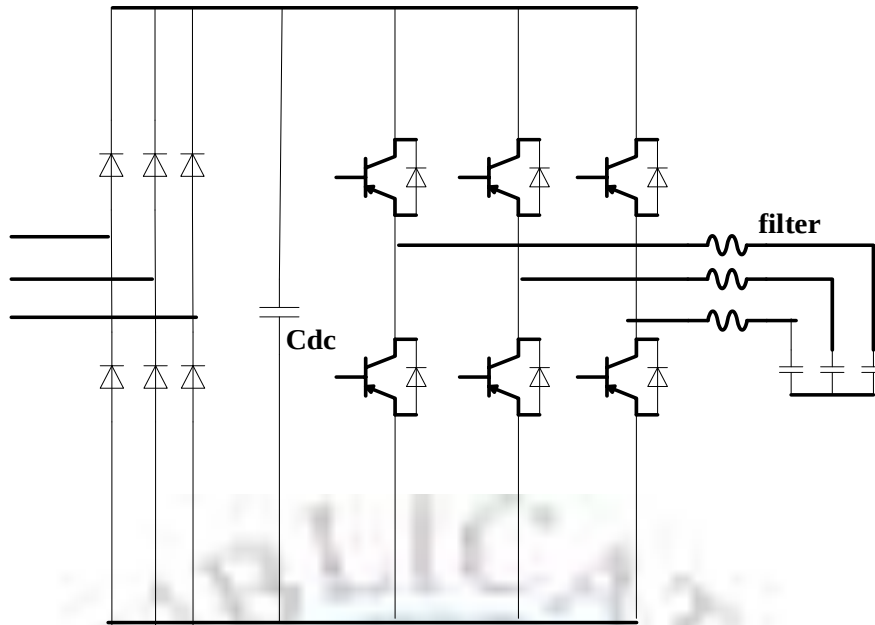


Figure 2. Diode rectifier and VSI circuit for VSWT modeling

D. Power Electronic Control

Several types of power electronics interfaces have been investigated for variable speed wind turbine [7], [11]. This section addresses a power conversion system composed of a six-diode rectifier and six-IGBT voltage source inverter, which is simple, cost-effective and widely used for industrial applications. The VSI includes a LC harmonic filter at its terminals to reduce harmonics it generates. Fig.2 presents a rectifier and VSI model of the studied VSWT. The rectifier converts ac power generated by the wind generator into dc power in an uncontrollable way; therefore, power control has to be implemented by the VSI. A current-controlled VSI can transfer the desired real and reactive power by generating an AC current with a desired reference waveform [12]. VOC (voltage oriented control) is used to control inverter with decoupled controller [13]. To further investigate the VOC scheme, the state equation for grid side circuit of the inverter in the ABC stationary reference frame can be expressed as (9), (10) and (11).

$$\frac{di_{ag}}{dt} = \frac{v_{ag} - v_{ai}}{L_g} \quad (9)$$

$$\frac{di_{bg}}{dt} = \frac{v_{bg} - v_{bi}}{L_g} \quad (10)$$

$$\frac{di_{cg}}{dt} = \frac{v_{cg} - v_{ci}}{L_g} \quad (11)$$

These equations (9), (10), (11) can be transformed into the dq synchronous reference frame by (12), (13)

$$\frac{di_{dg}}{dt} = \frac{v_{dg} - v_{di} - \omega_g L_g i_{dg}}{L_g} \quad (12)$$

$$\frac{di_{qg}}{dt} = \frac{v_{qg} - v_{qi} - \omega_g L_g i_{qg}}{L_g} \quad (13)$$

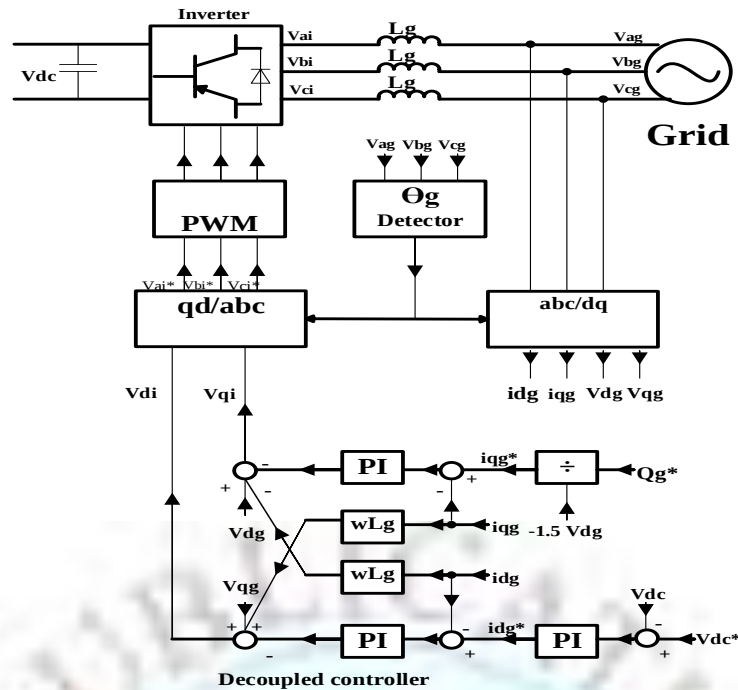


Figure 3. VOC with Decoupled controller

Where ω_g is the speed of the synchronous reference frame, which is also the angular frequency of grid, and $\omega_g L_g i_{dg}$ and $\omega_g L_g i_{qg}$ are induced speed voltage due to the transformation of the three-phase inductance L_g from the stationary reference frame to the synchronous frame. Equations (12), (13) illustrate that the derivative of the d-axis line current i_{dg} is related both to d-axis and q-axis variables, as is the q-axis current i_{qg} . This indicate that the control system is cross-coupled, which may lead to difficulties in controller design and unsatisfactory dynamic performance. The problem can be resolved by using a decoupled controller as shown in Fig.3.

E. STATCOM and SVC Model

FACTS devices in power transmission systems allow maximum use of the capabilities of the system, by adding a strong control system to the grid with various control parameters. These devices are equipment in which the controller is given based on power electronic. These equipment are used in the AC transmission systems to increase the controllability of the system, increase the power transfer capability, improve the voltage control and reactive power compensation and also to overcome the limitations of the transmission lines. Advantages gained by using FACTS devices in power transmission systems are as follows:

- Better Load flow control
 - Increasing the capacity of transmission lines towards their thermal capacity
 - Improved voltage control and reactive power compensation
 - Increased dynamic stability
 - Improved power quality
 - Ability to control system parameters
 - Increasing the efficiency of new and old lines builder
- FACTS systems are generally divided into four categories [6]:
- Series controller
 - Parallel controller
 - Series-series controller
 - Parallel-series controller

From a variety of parallel FACTS devices, one can recall SVC and STATCOM, which are used in this paper to improve the voltage and power quality.

1) SVC

Static Var Compensators (SVC), unlike synchronous condensers, are reactive compensators without rotor; thus are called static. The main task that SVC can do is the bus voltage regulation by controlling the reactive power at the point. In this paper, a combination of TC and TSC has been used as SVC to control both in capacitive and inductive mode [12]. Fig.4 shows this SVC arrangement.

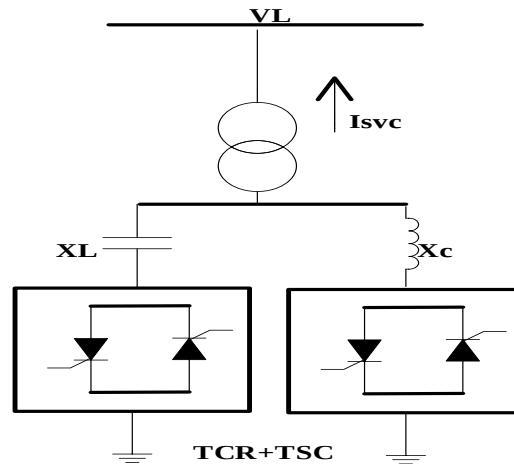


Figure 4. SVC model

The SVC is actually an example of parallel FACTS devices used for compensating reactive power and voltage regulation during and after the faults. Thus, the SVC can increase system stability. For closed-loop control, voltage is measured and compared with a reference value and an error signal is generated. This error signal is sent to a PI controller to the firing angle of TCR and TSC number of steps to determine the firing angle. The firing angle pulse generator for generating a pulse is sent to the fire. Fig. 5 shows the SVC control scheme.

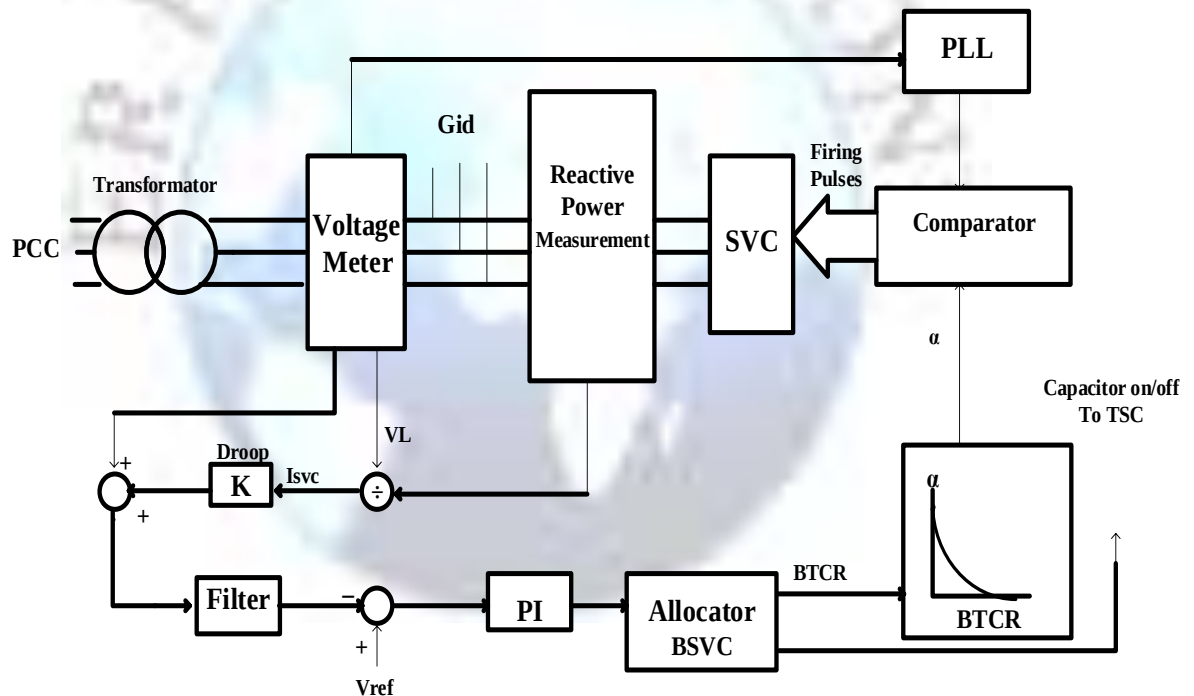


Figure 5. SVC control scheme

2) STATCOM

Restrictions caused by natural commutation static SVC as a high-volume, high-cos and progress will lead to a new class of power electronic elements SVC, which is based on the forced commutation [8]. This new class initially was known as static reactive power compensator developed that now is called STATCOM. The capabilities of the STATCOM are lower than the SVC due to smaller capacitor used in it. In this paper, the STATCOM is modeled using IGBT and DC link capacitors. The STATCOM controller is shown in Fig. 6. DC voltage is controlled by changing M_0 . AC generator voltage is compared to a reference voltage to produce the modulation index. PLL is synchronizing the control signal to the voltage grid. With the construction of the reference signal M_m , these signals are compared with the carrier signal, and make gate pulses of the IGBTs.

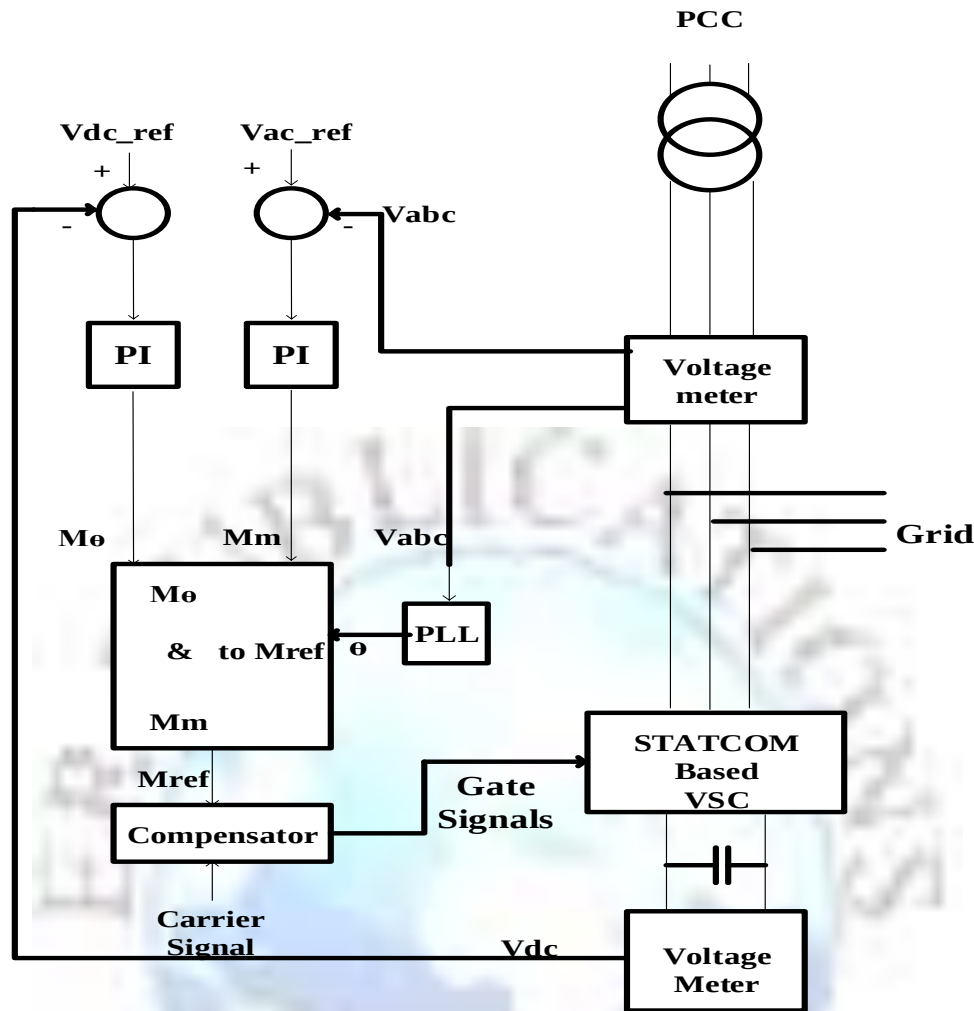


Figure 6. STATCOM control scheme

III. Simulation and Result

The proposed model is implemented into PSCAD/EMTDC software and simulated for analyzing the dynamic behavior of a wind turbine with varying wind conditions. The wind turbine of 1MW rating has been connected to distribution feeders through a 0.69/22.9 kV transformer. The rating of inverter is 1.2MVA and PWM switching frequency is 3.6 kHz. The short circuit capacity of the 22.9-kV bus is 68.4MVA. The X/R ratio of the bus impedance is 52-W. To compare the desired performance of STATCOM and SVC regarding voltage control, they are added to PCC bus in-turn and then, a 3-phase fault is simulated at PCC bus at second one and is removed after 10 milliseconds.

1) Connection of STATCOM to PCC Bus

The proposed model with STATCOM in PCC bus is implemented in PSCAD/EMTDC as illustrated in Fig. 7. Wind speed condition is presented in Fig. 8. Fig.9, Fig. 10 and Fig. 11 respectively illustrate PCC bus voltage, active power and reactive power in the normal state (without fault). Three phase fault is applied on the PCC bus at second one and is removed after 10 milliseconds. PCC bus voltage in the three phase fault state without STATCOM is illustrated in Fig. 12. Fig. 13, Fig. 14 and Fig. 15 respectively illustrate PCC bus voltage, active power and reactive power with STATCOM under fault conditions.

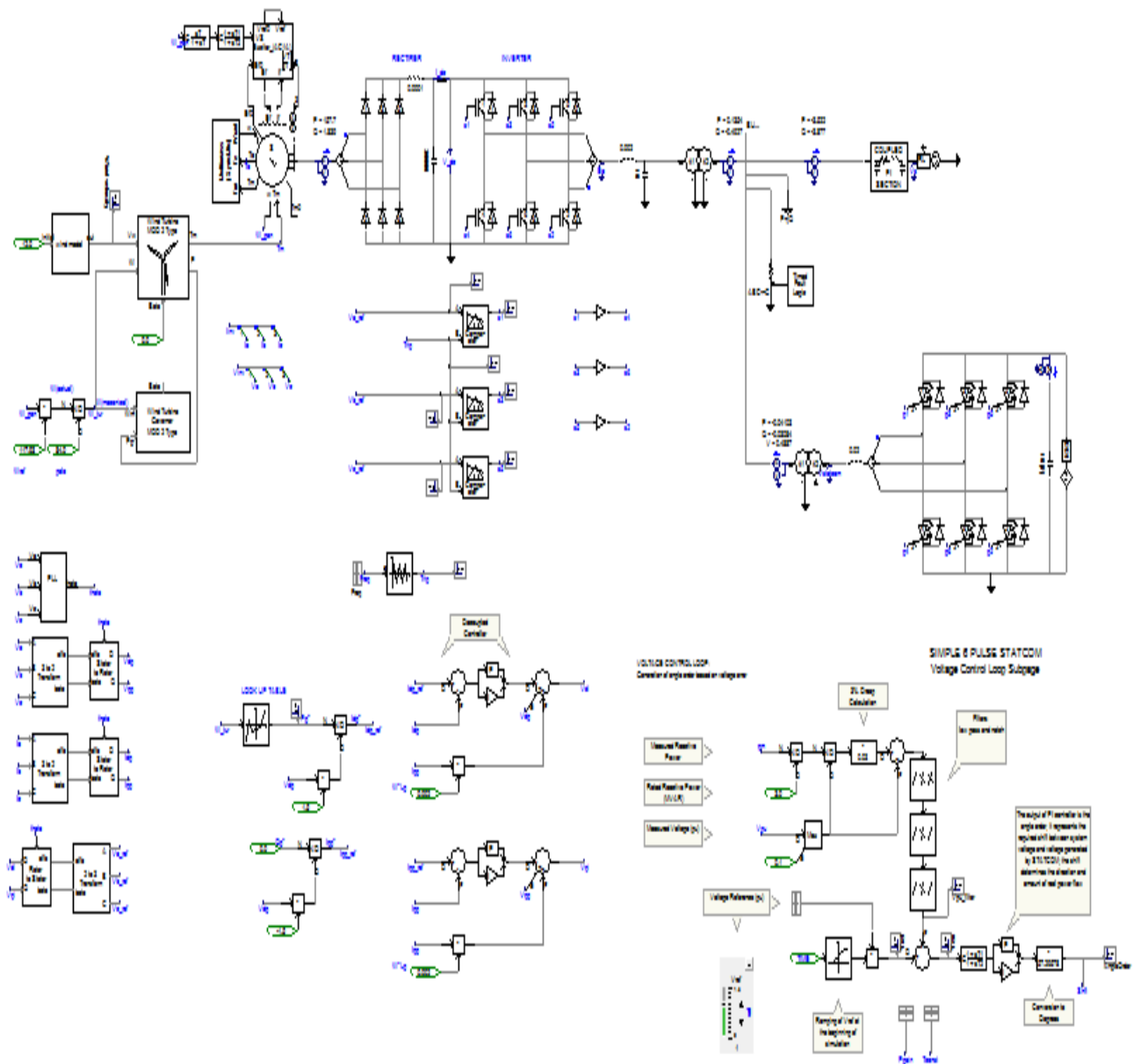


Figure 7. VSWT with STATCOM implemented in PSACD/EMTDC

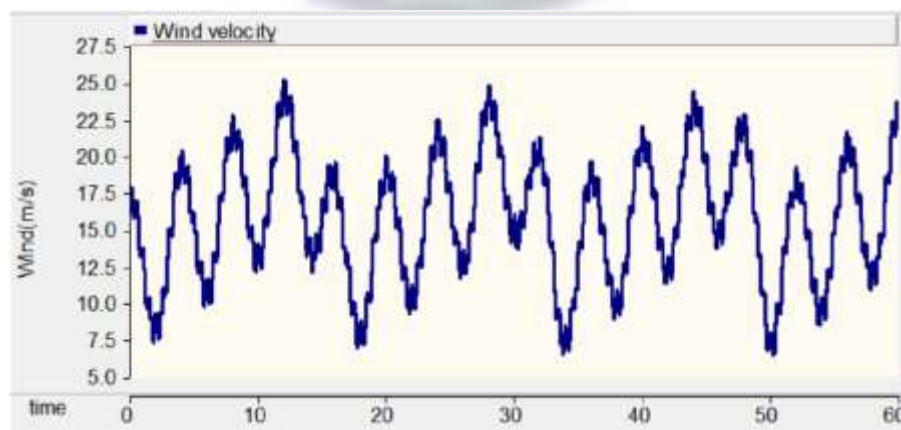


Figure 8. Wind speed

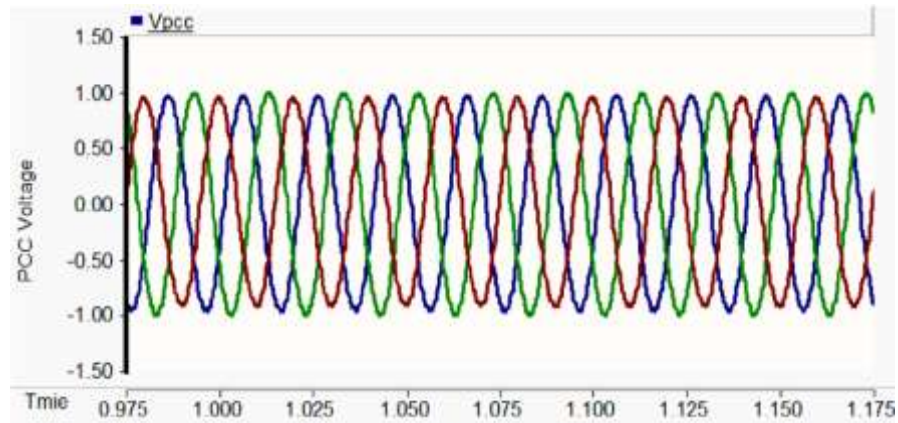


Figure 9. PCC voltage in the normal state

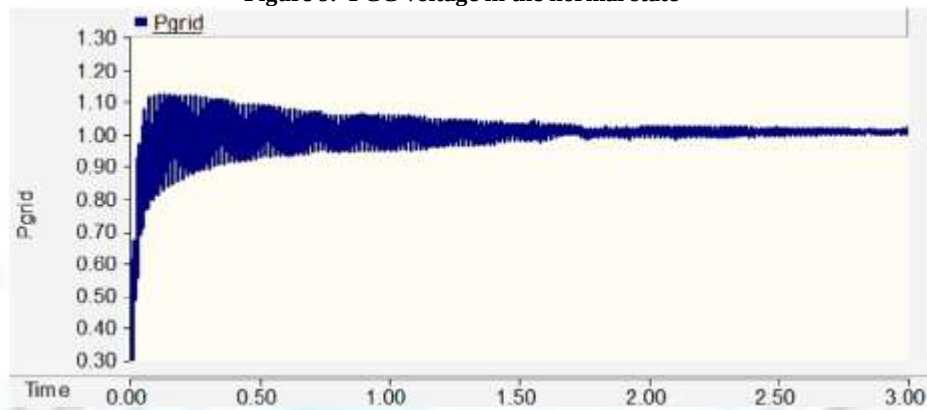


Figure 10. PCC active power in the normal state

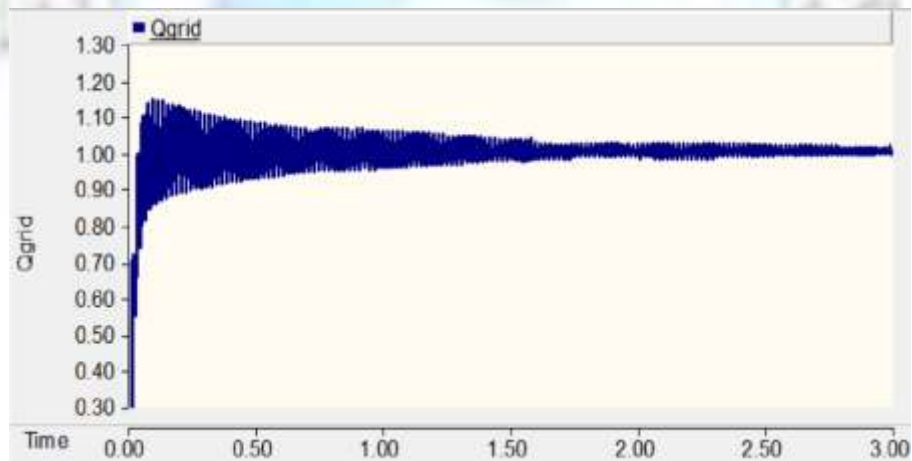


Figure 11. PCC reactive power in the normal state

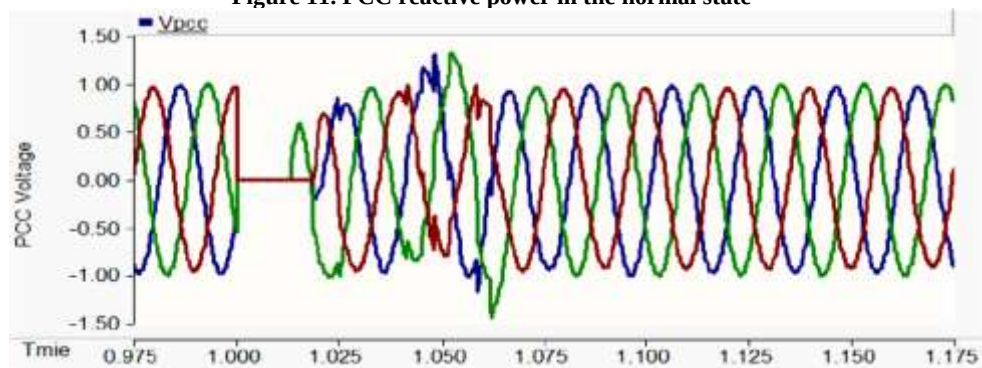


Figure 12. PCC voltage in the three phase fault state, without STATCOM

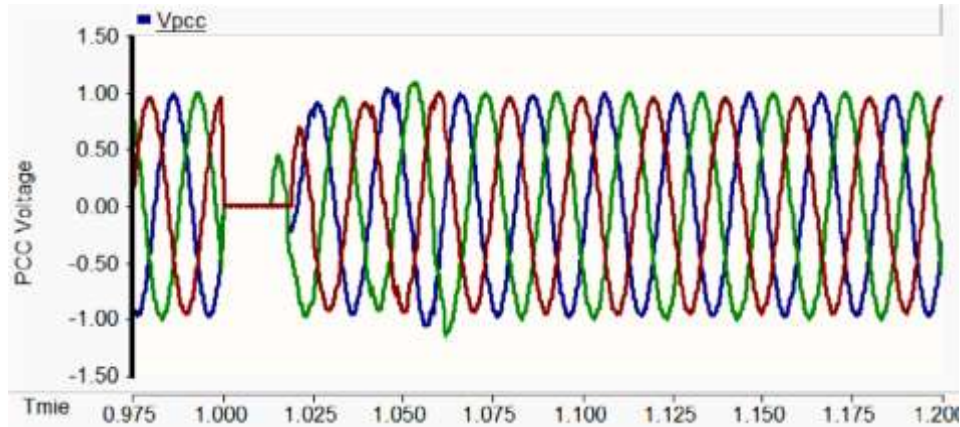


Figure 13. PCC voltage with STATCOM in the three phase fault state

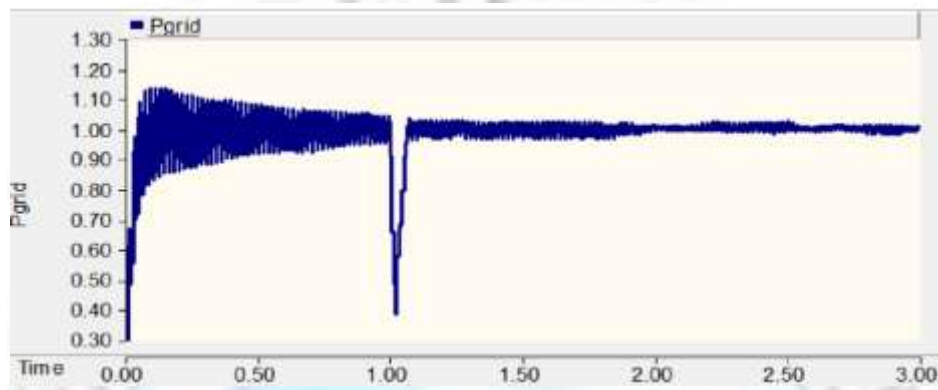


Figure 14. PCC active power with STATCOM in the three phase fault state

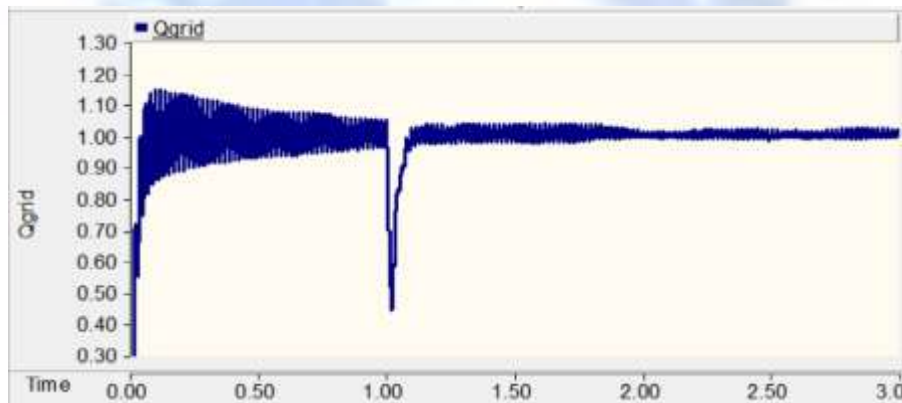


Figure 15. PCC reactive power with STATCOM in the three phase fault state

2) Connection of SVC to PCC Bus

The proposed model with SVC in PCC bus is implemented in PSCAD/EMTDC as illustrated in Fig. 16. The PCC bus voltage, active power and reactive power in the normal state are as shown in Fig.9, Fig. 10, Fig. 11 respectively. Three phase fault is applied on the PCC bus at second one and is removed after 10 milliseconds. PCC bus voltage in the three phase fault state without SVC is illustrated in Fig. 12. Fig. 17, Fig. 18 and Fig. 19 respectively are illustrating Three phase fault is applied on the PCC bus at second one and is removed after 10 milliseconds. PCC bus voltage, active power and reactive power with SVC.

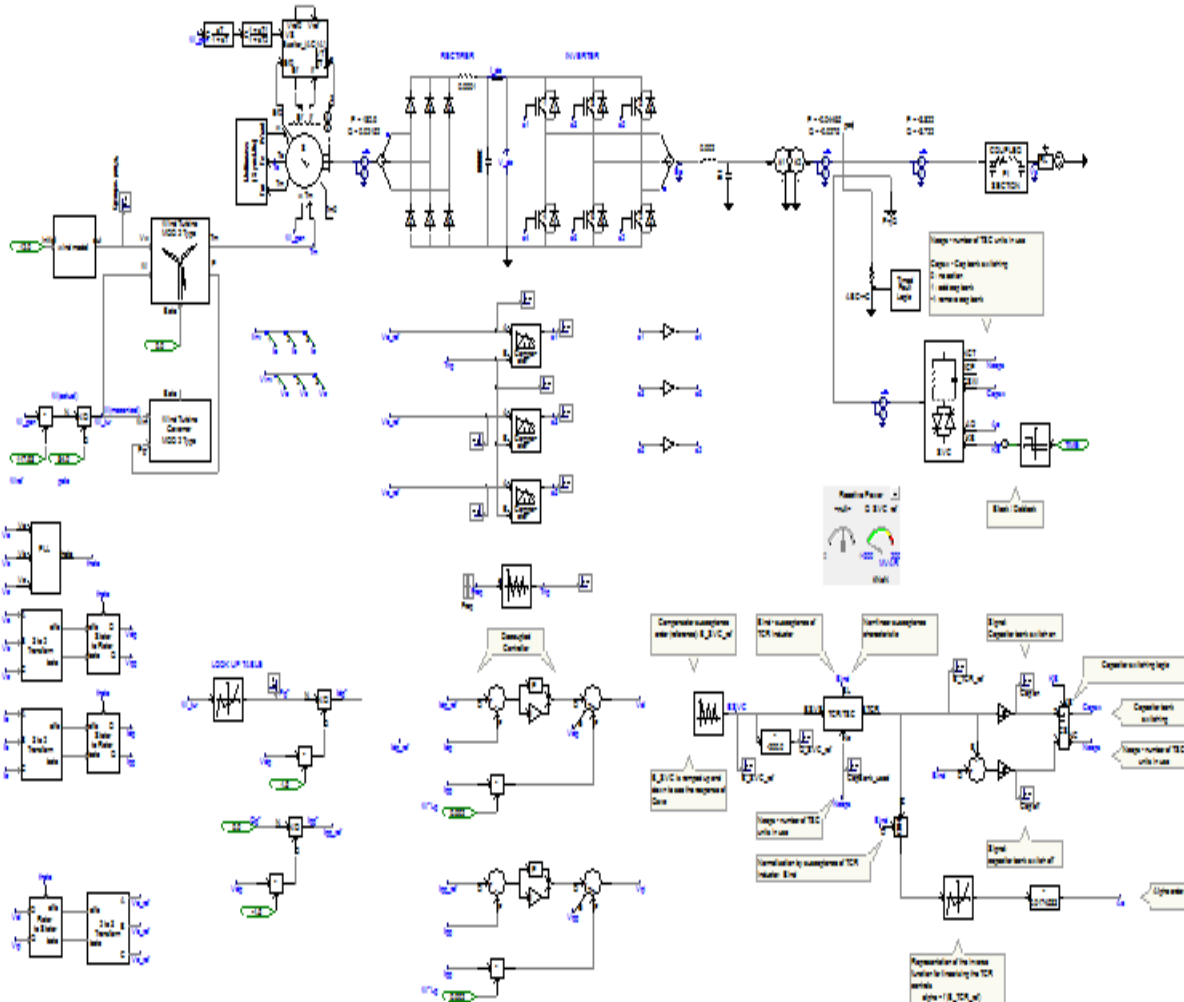


Figure 16. VSWT with SVC implemented in PSACD/EMTDC

Comparing Fig.13 and Fig. 17 to Fig 12, voltage waveforms improvement by using STATCOM or SVC becomes evident. However, it is quite clear that STATCOM is more effective than SVC in improving the voltage waveforms. Also, Fig. 14, Fig. 15, Fig. 18 and Fig. 19 show improvements in active power and reactive power by using STATCOM or SVC in the PCC bus. Finally it can be stated that STATCOM brings more stability of voltage and power delivery to grid than SVC.

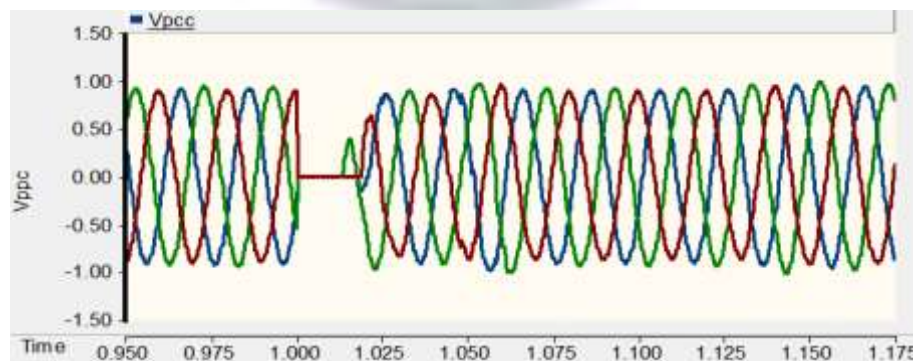


Figure 17. PCC voltage with SVC in the three phase fault state

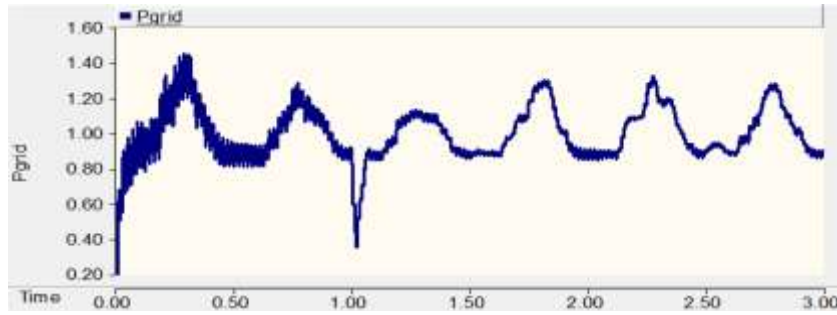


Figure 18. PCC active power with SVC in the three phase fault state

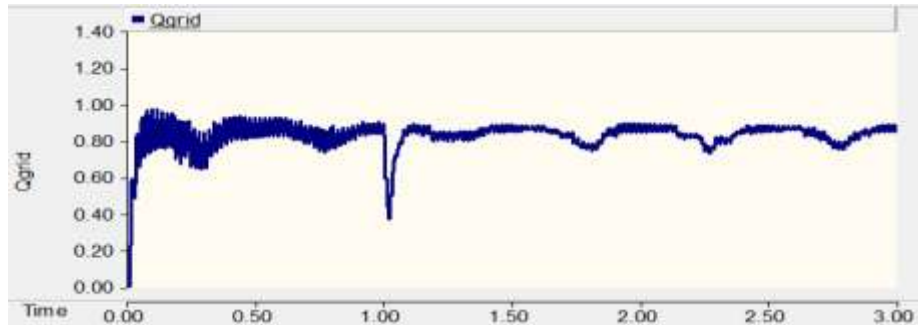


Figure 19. PCC reactive power with SVC in the three phase fault state

Conclusion

A dynamic model of a gearless VSWT with dc link converter and VOC-Decoupled control strategy equipped with STATCOM or SVC and proposed for computer simulation study was implemented in a reliable power system transient analysis program, PSCAD/EMTDC. In presence of STATCOM or SVC, the three phase fault impact on the quality of voltage and power at PCC bus was studied. It was realized that the presence of STATCOM or SVC improve the voltage delivered to the grid. The obtained results demonstrate improving of the voltage and power with STATCOM or SVC than. Although, STATCOM has more favorable effect than SVC on improvement of VSWT output voltage and damping three phase fault oscillations.

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