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POWER QUALITY IMPROVEMENT FOR GRID CONNECTED SYNCHRONOUS GENERATOR BASED WIND FARM

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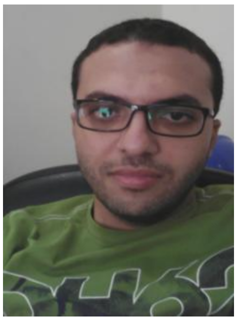


KARIM MOHAMED GAMAL

ABSTRACT

In this paper, we revise the power quality issues of grid connected synchronous generator(SG) based wind farm. Firstly, the model of wind energy conversion system(WECS) was modeled using MATLAB simulink. The system consists of turbine, gearbox, DFIG and converters. The total harmonic distortion (THD) index was used as performance index for both wind farm output voltage and current. THD was performed using Fast Fourier Transform(FFT) technique. Static synchronous compensator(STATCOM) and static var compensator(SVC) was applied for improving THD and therefore the system dynamic response.

Key words: Synchronous generator(SG), power quality (PQ), Total harmonic distortion(THD) , STATCOM, SVC.

Nomenclature:

C_p: Power coefficient.
λ : Tip speed ratio.
β: pitch angle(rad).
ρ: Air density(kg/m^3).
A: Area swept by turbine blades(m^2).
V: Velocity of wind (m/s).
ω_t: Angular velocity of wind (rad/s).
R: Radius of wind turbine blade (m).
T_t: Turbine torque (N.m).
P_t: power of turbine (W).
T_g: Torque of generator (N.m).
G: gear ratio.

1. INTRODUCTION

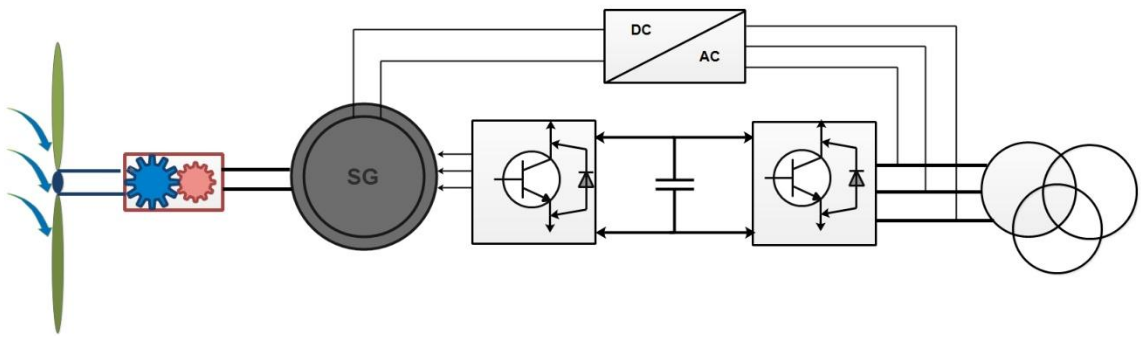
Wind energy is one of the most promising renewable energy sources due to the progress experienced in the last decades. Governments are attracted by the wind energy conversion system (WECS) with simple structure, easy maintenance and management. According to new and renewable energy association (NREA) of Egypt, renewable energy share will reach 20% of the total generated energy by 2020,12% of it will be of wind energy[1].

Wind energy is playing a major role in the effort to increase the share of renewable energy sources in the world energy mix helping to satisfy global energy demand.

During the last decades, WECS has grown very fast. Variable-speed wind turbines (VSWTs) attract considerable interest around the world, which is one of the solutions with the highest potential to reduce wind energy cost. The VSWT systems are usually based on doubly fed induction generators(DFIGs), permanent magnet synchronous generators (PMSGs), squirrel cage induction generator with full scale converter or synchronous generator with full scale converter[2,8].

In this paper , the SG was chosen , and the study of the power quality of the wind farm connected to the grid was carried out. Even though wound-rotor synchronous generators, shown in figure(1), are not so common, they are becoming a viable alternative because of grid-code requirements, such as voltage support during fault conditions; control of reactive power in a given range, limiting maximum power generation and start-up current transients.

Synchronous generator are widely used in stand-alone WECS where the synchronous generator can be used for reactive power control in the isolated network. To ensure the wind turbine connection to the grid a back-to-back PWM voltage source inverters are interfaced between the synchronous generator and the grid. The grid side PWM inverter allows for control of real and reactive power transferred to the grid. The generator side converter is used for electromagnetic torque regulation [3]. Synchronous generators of 500 kW to 2 MW are significantly more expensive than induction generators with a similar size. One should note that the use of a multipole synchronous generator (large diameter synchronous ring generator) avoids the installation of a gearbox as an advantage but a significant increase in weight will be accepted in counterpart. Indeed, the industry uses directly driven variable speed synchronous generators with large-diameter synchronous ring generator. The variable, directly driven approach avoids the installation of a gearbox, which is essential for medium and large-scale wind turbines.



Figure(1) SG wind turbine system

Synchronous generator with slip rings was used. In this system, rotor is fed from an AC to DC converter to supply DC power required for DC field of synchronous generator. The stator is connected to the B575 through the use of two voltage-source converters linked via a capacitor, thus allowing variable speed operation, reduction of mechanical stress; higher overall efficiency, reduced acoustical noise.

The WECS will be modeled in MATLAB Simulink environment and the quality of power produced from 10MW wind farm will be shown. The power quality studies are of importance to wind farm because the individual wind turbine can be sized up to 5MW, feeding into distribution network with high source impedance and with customer connected in close proximity.

The existence of international standards is a major contribution to assess and increase the power quality of grid connected wind turbines, especially in what concerns the assessment of the impact that different technologies may have in weak sensitive systems. The necessity to regulate the grid connection of wind turbines and its impact on the local consumers was recognized by the IEC that published standard – IEC 61400-21: “Measurement and assessment of power quality characteristics of grid connected wind turbines”. In this standard, the main parameters and constraints that characterize the wind power quality are identified, some specific test methodologies to apply to WECS are established[4].

This paper demonstrates that the power electronic based power conditioning using custom power devices like STATCOM and SVC can be effectively utilized to improve the quality of power produced from the wind farm.

2. Modeling of the wind energy conversion system

Modeling of the wind turbine and the gear box

The wind turbine system converts the power from the kinetic energy of the flow of the wind to the rotational movement of the shaft. The wind turbine power is given as follow [9]

$$P_t \frac{1}{2} C_p(\lambda, \beta)\rho\, AV^3 \quad (1)$$

The wind turbine has the ability to convert only fraction of the wind power, this fraction is called the power coefficient or Betz's factor and is dependent on the wind speed, the pitch angle of the blades and the tip speed ratio.

Tip speed ratio is the ratio between the angular velocity of the turbine multiplied by turbine radius and the speed of the wind

$$\lambda = \frac{\omega_t\, R}{V_w} \quad (2)$$

For any wind turbine, there is a value of tip speed ratio at which Cp is maximum which accordingly maximizes the power obtained at a given wind speed.

The turbine torque is the ratio between the power of turbine to the speed of turbine

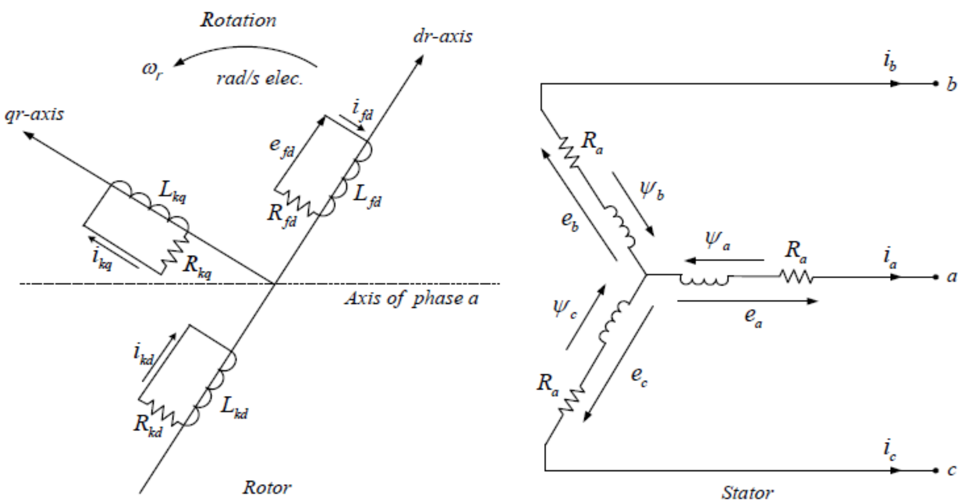
$$T_t = \frac{P_t}{\omega_t} \quad (3)$$

The turbine shaft is connected to the generator via a gear box with gear ratio G so that it sets the generator speed within certain desired range.

$$T_g = \frac{T_t}{G} \quad (4)$$

$$\omega_t = \frac{\omega_g}{G} \quad (5)$$

The core equations of the electric generator model can be obtained from the rotor and stator circuits depicted in Figure 3.13. Circuits comprehend the stator winding and the rotor windings: field winding and two damping windings (kd, kq). Coefficients of these equations are made constant through the Park´s transformation. Then equations are normalized[6]:



Figure(2) Rotor and stator circuits of a three-phase synchronous generator

Stator equations in dq0 coordinates:

$$e_d = p\psi_d - \psi_q\omega_r - R_a i_d \quad (6)$$

$$e_q = p\psi_q + \psi_d\omega_r - R_a i_q \quad (7)$$

$$e_0 = p\psi_0 - R_a i_0 \quad (8)$$

$$\psi_d = -L_d i_d + L_{afd} i_{fd} + L_{akd} i_{kd} \quad (9)$$

$$\psi_q = -L_q i_q + L_{akq} i_{kq} \quad (10)$$
$$\psi_0 = -L_0 i_0 \quad (11)$$

Rotor equations in dq0 coordinates:

$$e_{fd} = p\psi_{fd} + R_{fd} i_{fd} \quad (12)$$
$$0 = p\psi_{kd} + R_{kd} i_{kd} \quad (13)$$
$$0 = p\psi_{kq} + R_{kq} i_{kq} \quad (14)$$
$$\psi_{fd} = L_{ffd} i_{fd} + L_{fkd} i_{kd} - \frac{3}{2} L_{afd} i_d \quad (15)$$
$$\psi_{kd} = L_{fkd} i_{fd} + L_{kkd} i_{kd} - \frac{3}{2} L_{akd} i_d \quad (16)$$
$$\psi_{kq} = L_{kkq} i_{kq} - \frac{3}{2} L_{akq} i_q \quad (17)$$

Since the connection of the synchronous generator to the AC/DC/AC power converter is balanced, the electric power output P_e can be calculated as:

$$P_e = \frac{2}{3}\left(e_d i_d + e_q i_q\right) \quad (18)$$

Finally, the excitation system is a simplified version of the IEEE AC4A exciter (IEEE 421.5, 1992) with transfer function:

$$e_{fd} = \frac{200}{0.04S + 1} V_R \quad (19)$$

3. Power quality issues of wind energy conversion system

Power injection from grid-connected wind turbines affects substantially the power quality. The procedures for the measurement and assessment of the main parameters involved in the power quality characteristics of a wind turbine are described in the IEC 61400-21 standard[10]. The tests are designed to be as non-site-specific as possible, so that power quality characteristics measured with the wind turbine connected at a test site can also be considered valid at other sites.

The validity of the measurement procedure is dependent upon the proper establishment of the test conditions. The wind turbine has to be directly connected to the MV-network and the measurements of the electrical characteristics have to be made at the wind turbine terminals.

It is necessary to specify the rated data of the wind turbine including rated active power of wind turbine P_n, rated apparent power S_n, nominal phase-to-phase voltage U_n and the rated current I_n. Moreover, the location of the wind turbine terminals and the specific configuration of the assessed wind turbine including the relevant control parameter settings have to be clearly stated in the test report.

According to the standard there are seven parameters compromising the required power quality characteristics of a wind turbine: voltage fluctuations or flicker; harmonics and inter-harmonics; voltage drops; active power; reactive power; grid protection and reconnection time. In this work we will describe THD of the waveforms refer to section 6.5 of reference[5].

Voltage and current harmonics are usually present on the utility network. Non-linear and electronic loads, rectifiers and inverters, are some sources which produce harmonic content.

The effects of the harmonics include overheating, faulty operation of protections, equipment failures or interferences with communication systems.

The standard specifically defines different procedures to assess the harmonics, inter-harmonics and higher frequency components for a wind turbine working under continuous conditions and operating with reactive power as close as possible to zero.

The values of the individual harmonics and higher frequency components and the Total Harmonic distortion (THD) must be provided in percentage of fundamental. The harmonic current components must be specified as sub-grouped RMS values for frequencies up to 50 times the fundamental grid frequency. The THD coefficient must be calculated from those values according to:

$$\mathrm{THD} = \sqrt{\sum_{h=2}^{50} x_{sg,h}^2 . 100}$$

where $x_{sg,h} = X_{sg,h}/X_n$ and $X_{sg,h}$ is the sub-grouped RMS harmonic of harmonic order h.

4. Power quality improvement

In the last two decades the commercial availability of Gate Turn-Off thyristor (GTO) devices with higher power handling capability, have led to the development of new controllable reactive power sources utilizing electronic switching of voltage source converter technology.

These facts technologies offer considerable advantages over the existing devices in terms of space reductions and fast controlling. The GTO switching devices enable the design of power electronic converters that can be either connected in parallel or in series with the power grids[7].

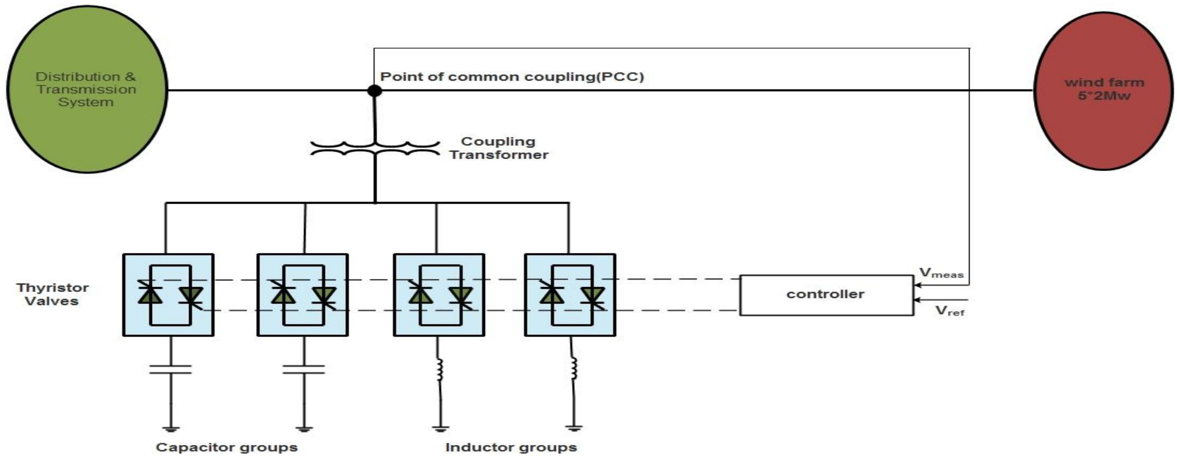
As a result of newly developed grid codes in countries with high penetration of wind power are becoming more demanding towards the operation of this source and as the WECS cannot achieve it by it's own, Therefore, additional equipment is needed in order to allow this technology satisfy the imposed requirements. Here, Flexible AC Transmission Systems (FACTS) play an important role[13].

Several distinctive devices can be classified under the name of FACTS. Among others, Static Synchronous Compensator (STATCOM), Static Var Compensator (SVC) and Static Synchronous Series Compensator (SSSC), appear as an adequate solution to the reactive power and voltage regulation conflicts of fixed-speed and variable-speed wind turbines[12].

These devices are able to interact with the system so as to improve the quality of the energy delivered to grid by the wind turbines and provide the low voltage ride through(LVRT) capabilities demanded by grid codes. According to their implementation, STATCOM and SVC can be defined as shunt-connected devices[11]. Application of STATCOM and SVC to wind farms has been addressed in the literature[18].

4.1 Static Var Compensator(SVC)

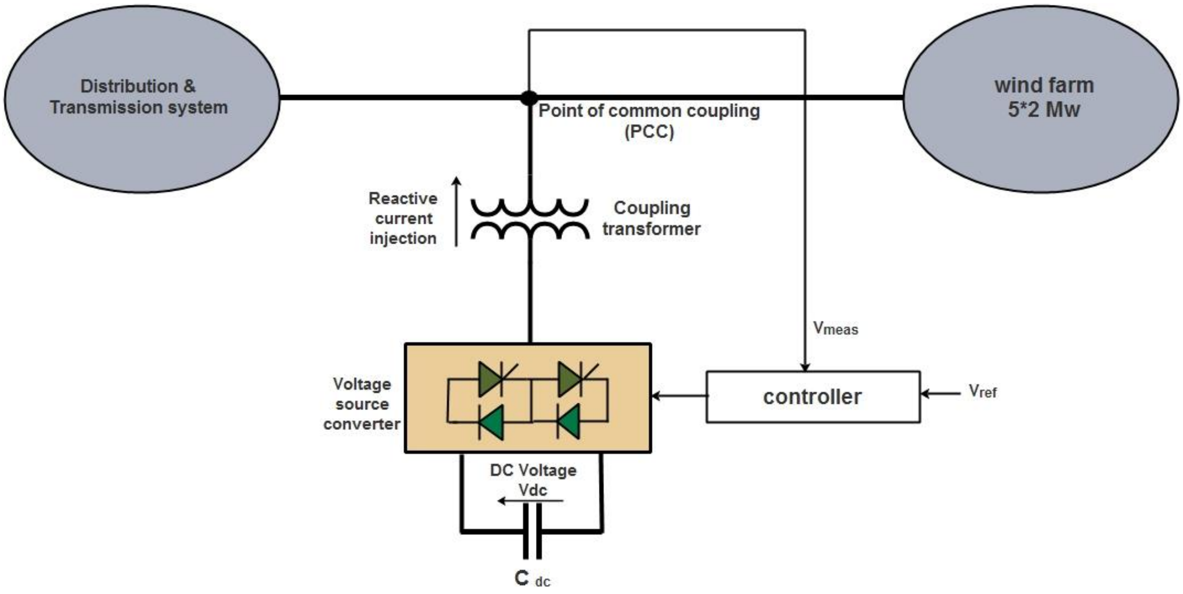
Static var compensator shown in figure(3), is one of the shunt compensating devices that can provide reactive power and support the system voltage which can be seen as a variable susceptance with a smooth control over a wide range from capacitive to inductive. The SVC consists of a number of thyristor switched capacitors (TSC) in parallel with a thyristor controlled reactor (TCR). The TSC provides step change of connected shunt capacitance while the TCR provides continuous control of the equivalent shunt reactance. SVC can be operated to provide reactive power control or closed loop AC voltage control[14].



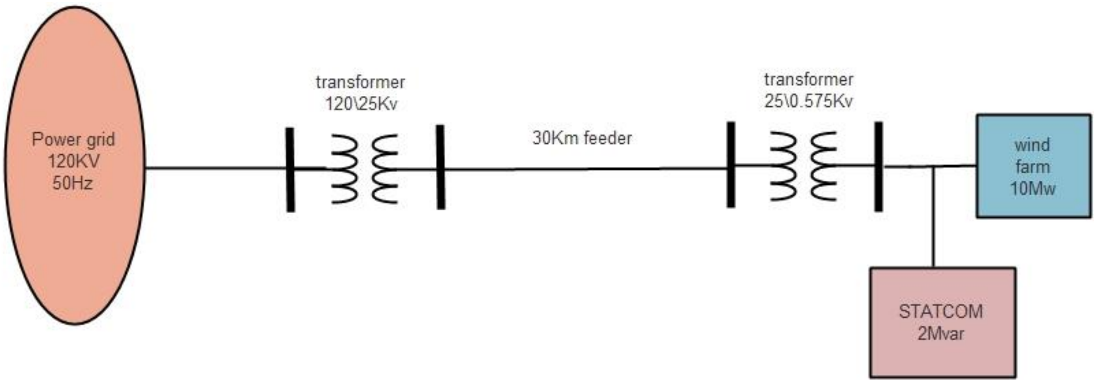
Figure(3) Static Var compensator schematic diagram

4.2 Static Synchronous Compensator(STATCOM)

Static synchronous compensator shown in figure(4) is another shunt compensating device which behaves like a synchronous voltage source which can inject or absorb reactive power. The STATCOM consists of a voltage source converter (VSC) and coupling transformer connected in parallel with the AC system. DC voltage of STATCOM is usually controlled to a fixed value so as to operate satisfactorily. Controlling the voltage generated by the converter to control the generated reactive power represents the basic operation of STATCOM[16]-[17].



Figure(4) STATCOM schematic diagram



Figure(5) detailed DFIG based wind farm connected to grid

5-Test model

The schematic diagram of the proposed system is modeled using MATLAB simulink and is shown in figure(5)

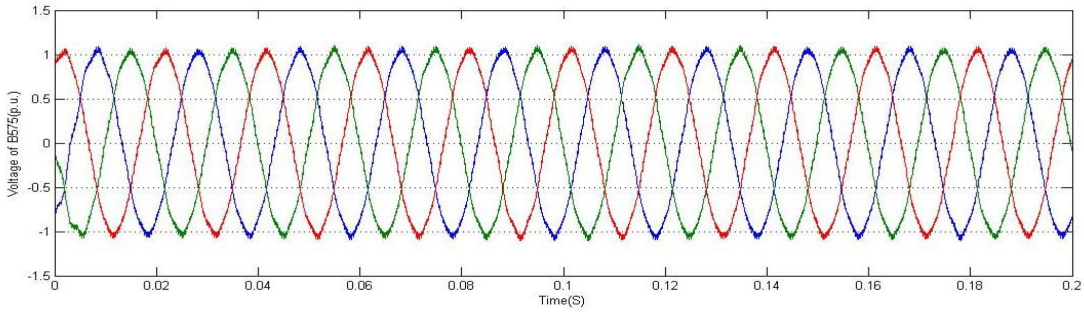
The system consists of 10Mw wind farm of 5 wind turbines each of 2Mw using DFIG connected to a 25 kV distribution system exports power to a 120 kV grid through a 30 km, 25 kV feeder.

Wind turbines using a wound rotor synchronous generator (WRSG) consist of a synchronous generator and an AC/DC/AC IGBT-based PWM converter. The stator winding isn't connected directly to the 50 Hz grid but the stator is connected through a AC/DC/AC converter so as to convert the output power of generator to a 50Hz power. The SG technology allows extracting maximum energy from the wind for variable wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind[19].

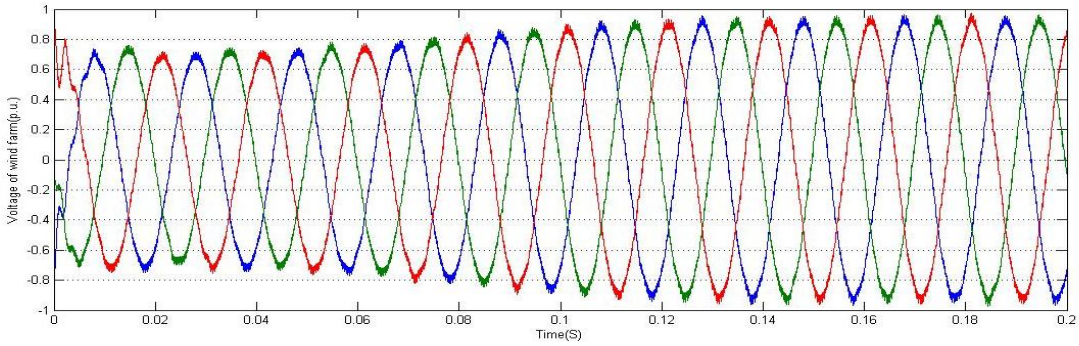
The grid is formed by a three–phase balanced programmable A.C voltage source at 120KV voltage. The 30 Km feeder lines were modeled as π-section. STATCOM or SVC are connected at PCC for reactive power compensation and power quality improvement.

6-Simulation results& discussion

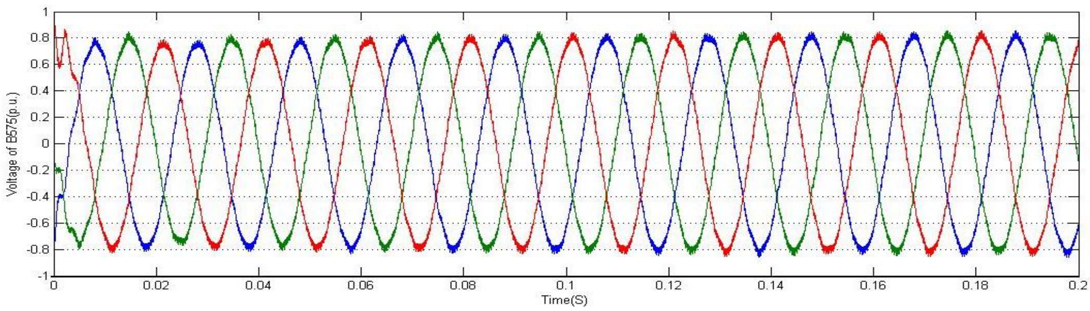
Case(1): THD analysis of the model without fault



(A) Without improvement



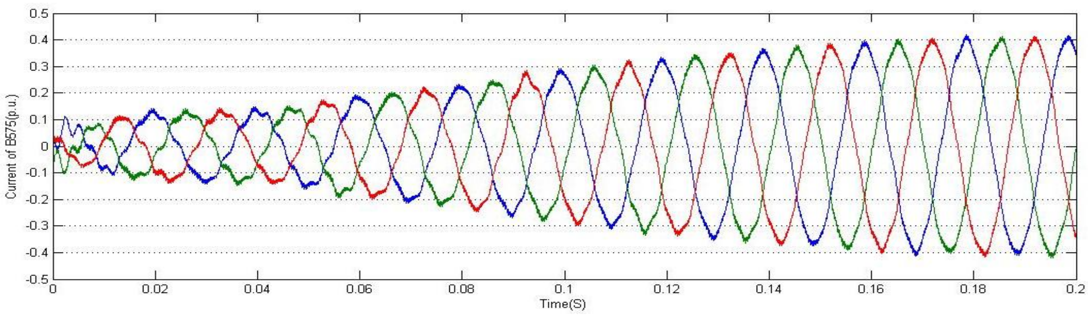
(B) With STATCOM



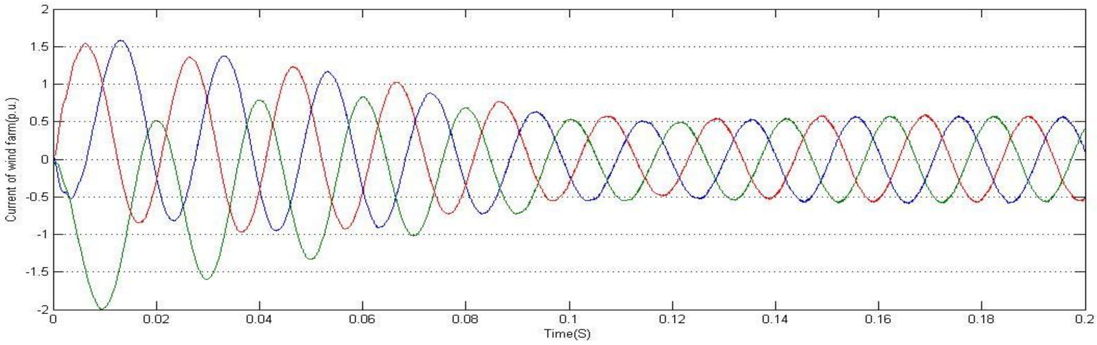
(C) With SVC

Figure (6) output voltage waveform of the wind farm in normal operation case with SG

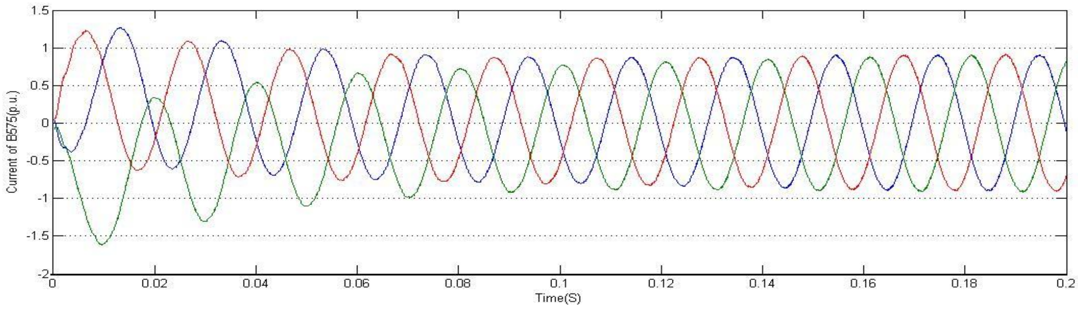
Figure(6) shows the voltage waveforms of the output voltage of B575 of the farm in normal operation, it is obvious that when there is no improving device connected the voltage's quality is good and the voltage stabilizes at value of 1.1p.u., when STATCOM is connected the voltage reaches steady state value of 0.95p.u.
when SVC is connected the voltage reaches steady state value of 0.85p.u.



(A) Without improvement



(B) With STATCOM

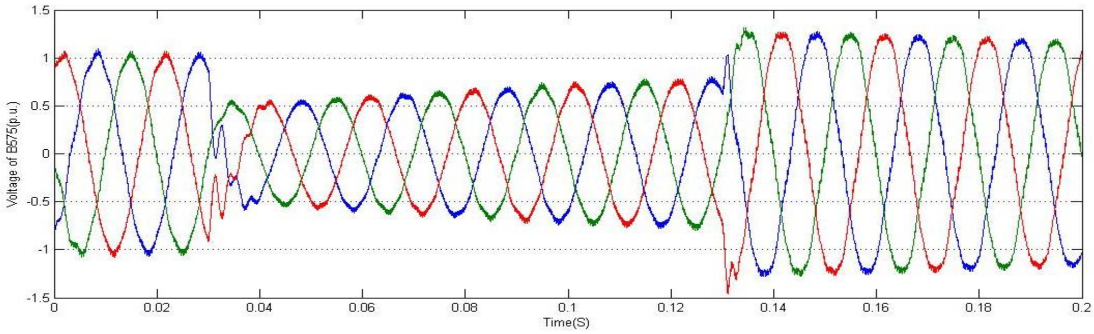


(C) With SVC

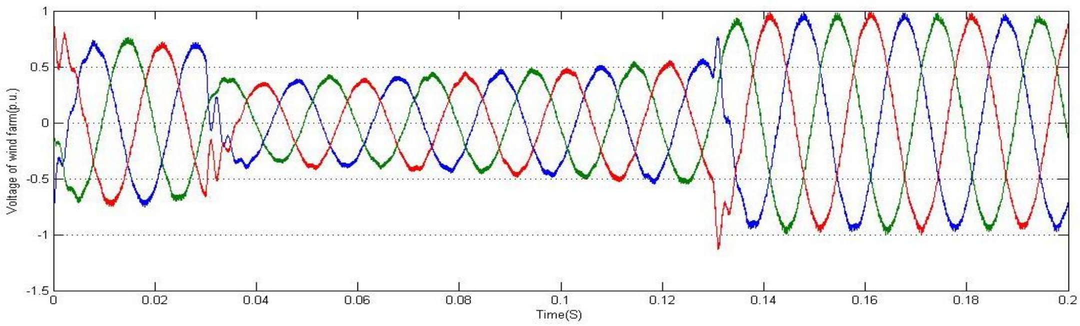
Figure (7)output current waveform of the wind farm in normal operation case with SG

Figure (7) shows the current output waveforms of B575 in normal operation case, it is obvious that the distortion of the waveform is improved when STATCOM or SVC is connected.

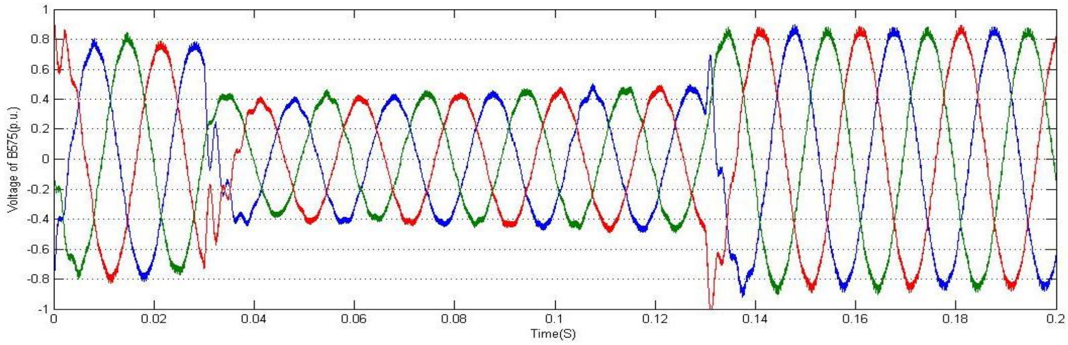
Case(2): THD analysis of the model with fault



(A) Without improvement



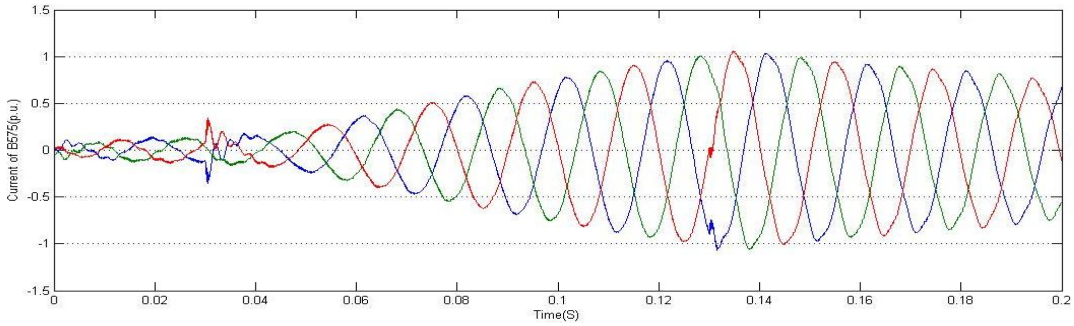
(B) With STATCOM



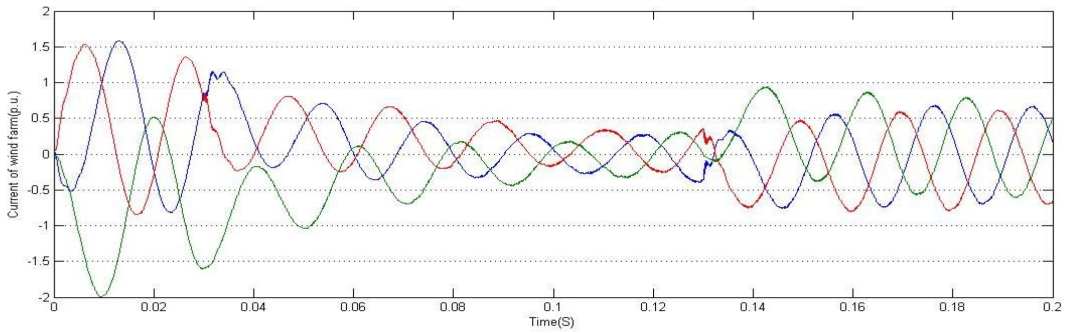
(C) With SVC

Figure (8) output voltage waveform of the wind farm in case of fault with SG

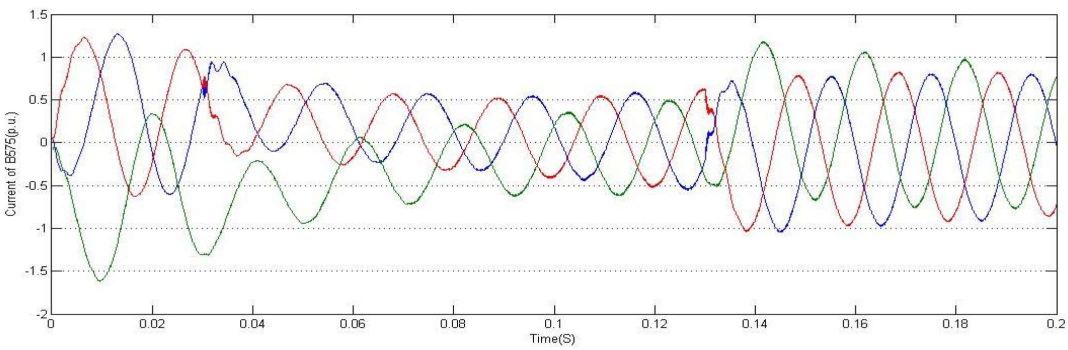
Figure(8) shows the output voltage waveform of B575 in case of occurrence of fault at grid side, the fault is initiated at t=0.03s and cleared at t=013s.



(A) Without improvement



(B) With STATCOM

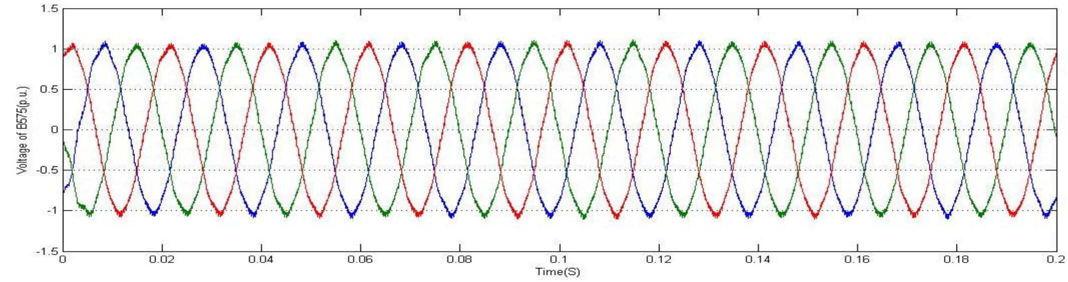


(C) With SVC

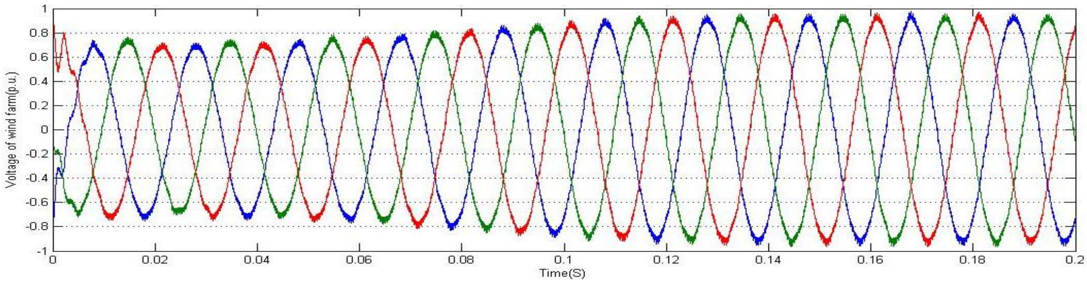
Figure(9) output current waveform of the wind farm in case of fault with SG

Figure(9) shows the output waveform of current of B575 in case of fault, at case(A) the current builds up until it reaches value of 1.1p.u. then starts to decrease to a value of 0.7p.u. at t=0.2s. At cases(B) and (C), STATCOM and SVC are added respectively, current builds up quickly with maximum over shoots of 2p.u. and 1.7p.u. respectively then starts to decrease during fault and increases again after fault clearing.

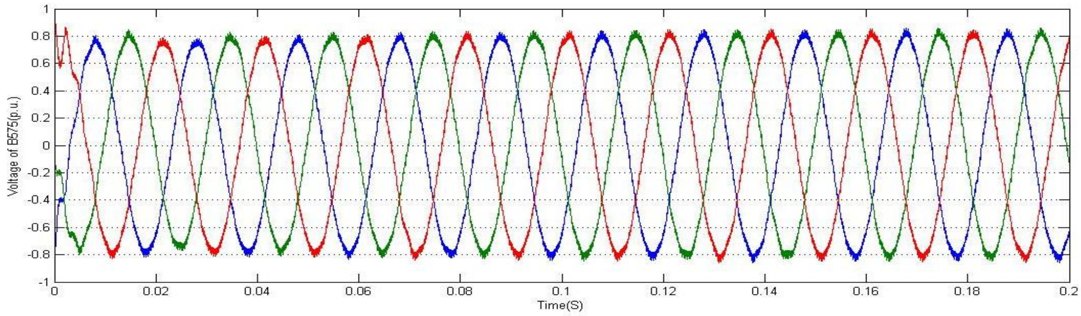
Case(3): THD analysis of the model with variable wind speed



(A) Without improvement



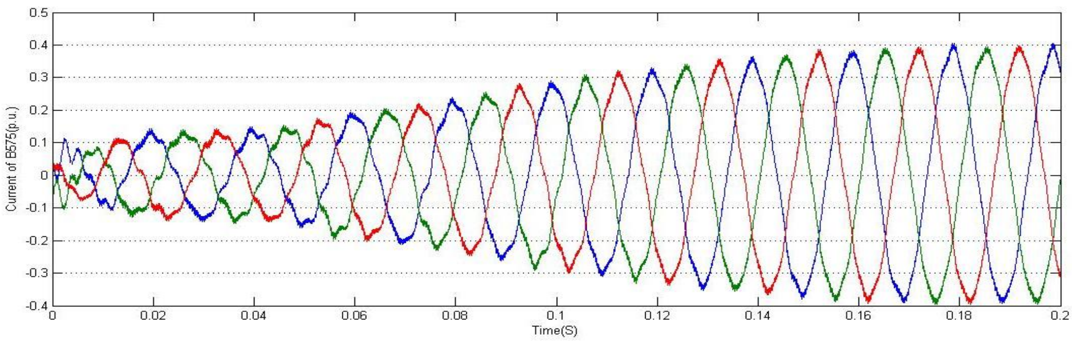
(B) With STATCOM



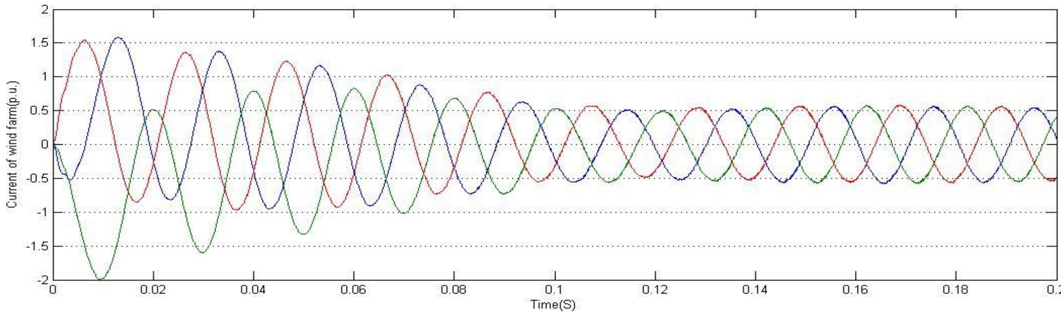
(C) With SVC

Figure (10) output voltage waveform of the wind farm in case of variable wind speed with SG

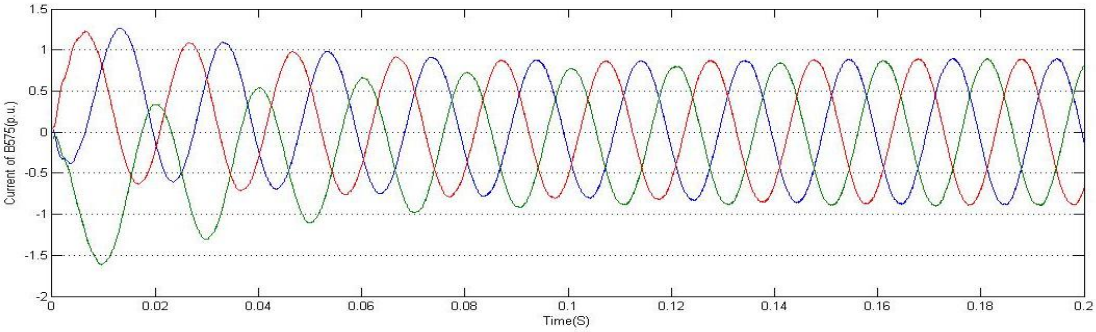
Figure(10) shows the output voltage waveforms of B575 in case of variable wind speed, the wind speed is dropped from 15m/s to 10m/s at t=0.03s then raises again to 15m/s at t=0.13s.



(A) Without improvement



(B) With STATCOM



(C) With SVC

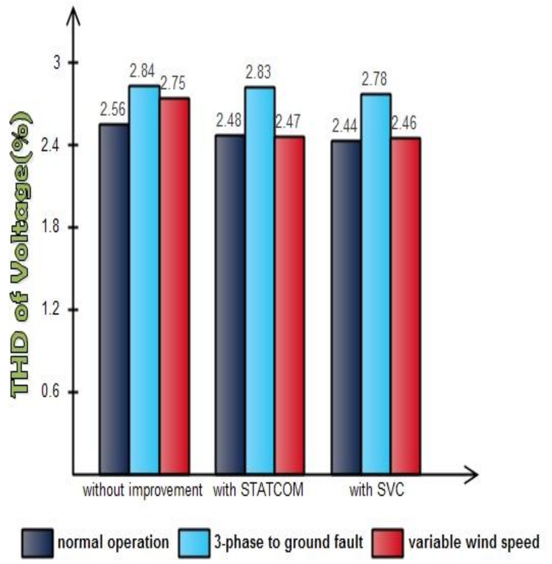
Figure (11) output current waveform of the wind farm in case of variable wind speed with SG

Figure(11) shows the output current wave form of B575 in case of variable wind speed, it is clear that the wave form is improved in both cases (B) and (C).

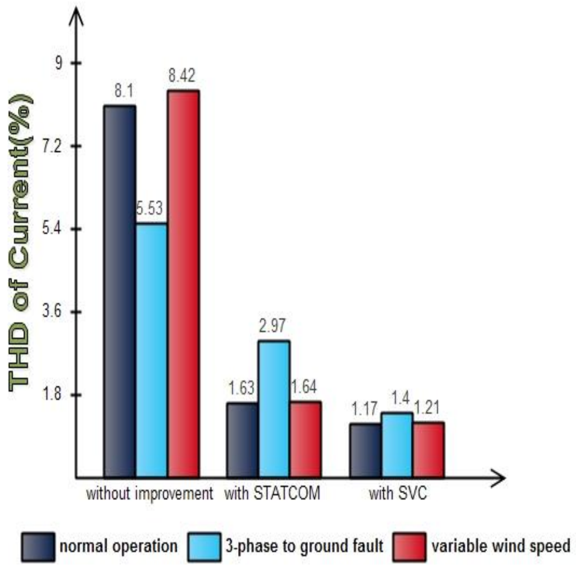
Table(1) The THD of voltage and current wave forms for different tested cases will be as follows:

	Without improvement		With STATCOM(2Mvar)		With SVC(2Mvar)	
	Voltage	Current	Voltage	Current	Voltage	Current
Normal operation	2.56	8.1	2.48	1.63	2.44	1.17
3-phase to ground fault	2.84	5.53	2.83	2.97	2.78	1.4
Variable wind speed	2.75	8.42	2.47	1.64	2.46	1.21

From the above shown results of total harmonic distortion index measured at B575, it is obvious that with the use of FACTS devices, THD index was improved. At normal operation case the effect of STATCOM appears in shrinking the THD of voltage to a value of about 96% of its original value, while current to a value of 20%. For same case but with SVC the THD of voltage was decreased to 95% of its original value, while current to 14%. At case 3-ph to ground fault case with STATCOM, the THD of voltage decreases to a value of 99% , while current to 53%. Similarly when using SVC, the THD of voltage decreased to 97%, while current to 25%. Finally at case of variable wind speed with STATCOM, the THD of voltage decreases to 89%, while that of current to 19%. For same case with SVC the THD of voltage decreased to 89%, while current to 14%. When comparing the different cases we find that SVC is better for improvement, especially for current where its significant effect appears.



(a)Voltage THD



(b)Current THD

Figure(24)THD index of B575V in percentage of fundamental for SG

7. Conclusion

The general trend in the whole world nowadays is to get benefit of renewable energy sources specially wind energy. using of modern WECS, which depends on power electronic devices, introduces harmonics into the grid. Also due to the varying nature of wind speed these introduces some power quality problems. Modeling of WECS wind farm based on SG indicates a reasonable THD index level with and without disturbances in the system. The usage of FACTS devices as STATCOM or SVC with PI controller cancel harmonic contents of the system and improve reactive power flow in the system. In future work, we can change type of generator used in WECS and see THD index , we can optimize the controller gains to improve FACTS interaction also we can use other modern control techniques for FACTS[15].

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