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Impact of Static Var Compensator (SVC) Tuned by Harmony Search Algorithms on Wind Energy Conversion System (WECS) Stability

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Abstract— This paper studies the effect of static var compensator (SVC) on stability of the wind energy conversion system (WECS) based on fixed speed induction generators (FSIG). Due to the nature of asynchronous operation, system instability of wind farms based on FSIG is largely caused by the excessive reactive power absorption by FSIG after fault due to the large rotor slip gained during fault. It was found that the SVC considerably improves the system stability during and after disturbances, especially when the network is weak. Moreover, this paper shows by using Harmony Search Algorithm (HS) and Self-Adaptive Global Harmony Search Algorithm (SGHS) instead of a Conventional Control Method for tuning the parameters of PI controller for SVC, the performance of the system with SVC is improved under different fault scenarios. MATLAB/Simulink based simulation is utilized to demonstrate the application of SVC in wind farm integration. it is also carried out to investigate the enhancement in performance of the WECS achieved with a PI Controller tuned by Harmony Search Algorithm as compared to a Conventional Control Method.

Index Terms— Induction Generators, Wind Power, Static Var Compensator (SVC), Voltage Control, System Stability, PID Controller, Harmony search algorithms.

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1 Introduction

The increasing rate of the depletion of conventional energy sources has given rise to an increased emphasis on alternative energy sources that come from natural resources such as sun and wind [1]. Wind energy is gaining momentum in this field of clean energy due to its relatively low cost. However, with an increasing share derived from wind power sources, large scale connection of wind farms to the system has brought in new challenges [1],[2],[3]. In recent years wind turbine technology has undergone rapid developments, growth in size and the optimization of wind turbines has enabled wind energy to become increasingly competitive with conventional energy sources [4].

Wind turbines using fixed speed induction generator (FSIG) provide a simple, rigid, ease of maintenance, and cost effective solution for wind farm integration and are therefore characteristic of the squirrel cage induction generator is that this type of generator always takes its magnetizing current from the grid and thus consumes reactive power, which is undesirable for the transmission system, particularly in the case of large turbines and weak distribution systems [5]. But this small inconvenience may be overcome by connecting well-fitted capacitors to its terminals. The problem associated with wind energy conversion system is the fact that, unlike other generation systems, the power inflow rate into wind turbines is not controllable and hence, the power generated and output voltage are variables[5]. Voltage stability and efficient fault ride through capability are the basic requirements for higher penetration [5]. Wind turbines are expected to provide high quality of supply by regulating the output voltage and frequency and uninterrupted operation under transient voltage conditions in accordance with the grid codes. Low-cost mechanical switched capacitor (MSC) banks and transformer tap changers (TCs) are conventionally used to address issues related to voltage control. Although these devices help in improving the power factor of wind turbine and provide steady-state voltage regulation, the power quality issues, such as power fluctuations, voltage fluctuations, and harmonics, cannot be solved satisfactorily by them because these devices are not fast enough [5]. Therefore, a dynamic shunt reactive power compensator is needed to address

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these issues more effectively. Flexible AC Transmission System (FACTS) devices such as the Static Var Compensator (SVC) and static synchronous compensator (STATCOM) are being used extensively in power systems as they significantly regulate the output voltage by supplying or absorbing reactive power, and improve system stability, especially in the weak distribution system[6].

HS algorithm, a meta-heuristic algorithm that mimics the improvisation process of musicians, has been used for optimization in a wide variety of problems [7],[8],[9] and shows several advantages, such as:

1. There is no need for initial settings of control variables. Also few mathematical operations are required.

2. No derivative operations are required as the search stochastic.

In this paper a comparative study of the dynamic performance for the system with SVC based on Proportional –Integral (PI) controller tuned by conventional method and a new meta-heuristic Algorithm known as harmony search (HS) algorithms is evaluated under application of different types of faults at different places.

2 Wind Energy Conversion System

2.1 Modeling of The Wind Turbine

Wind energy conversion system (WECS) converts kinetic energy of wind to mechanical energy by means of wind turbine rotor blades; then the generator converts the mechanical power to electrical power. The wind power depends on the swept area of the blade (A) and also is a function of the air density ρ and the wind speed v_w. The transmitted power Pm is generally deduced from the wind power using the power coefficient C_p, as[10]:

$$P_m = Cp(\lambda)\, A\, \rho\, v_w^3/2 \quad (1)$$

The power coefficient is a non-linear function of the tip speed-ratio λ, that depends on the wind velocity and the rotation speed of the shaft wt

$$\lambda = (R \times w_t)/(v_w) \quad (2)$$

where R represents the blade radius (m).

2.2 Modeling of the IG

The model of the induction generator can be developed in the synchronous reference (d–q) frame as follows[11],[12]:

$$Vds = Rs\, ids + \frac{d}{dt}(\psi ds) - \omega e\, \psi qs$$

$$Vqs = Rs\, iqs + \frac{d}{dt}(\psi qs) + \omega e\, \psi ds$$

$$Vdr = Rr\, idr + \frac{d}{dt}(\psi dr) - (\omega e - \omega r)\, \psi qr$$

$$Vqr = Rr\, iqr + \frac{d}{dt}(\psi qr) + (\omega e - \omega r)\, \psi dr \quad (3)$$

The stator and and rotor flux can be computed as functions of the d-and q-axes stator and rotor currents as follows:

$$\psi ds = Lls\, ids + Lm\,(ids + idr)$$

$$\psi qs = Lls\, iqs + Lm\,(iqs + iqr)$$

$$\psi dr = Llr\, idr + Lm\,(idr + ids)$$

$$\psi qr = Llr\, iqr + Lm\,(iqr + iqs) \quad (4)$$

2.3Modeling of SVC

Fig.(1). shows the configuration of the SVC .Basically it consists Thyristor Switched Capacitors (TSC) in shunt with a Thyristor Controlled Reactor (TCR). The SVC can be operated to provide reactive power control or closed-loop AC voltage control. For closed-loop AC voltage control, the line voltage, as measured at the point of connection, is compared to a reference value and an error signal is produced. This is passed to a PI controller to generate the required susceptance value. It is then transmitted to the non-linear admittance characteristic to generate the firing angle for the TCR and to determine the number of TSC stages required to be switched on. The firing angle is passed to the gate pulse generator, which then generates the firing pulse for the TCR [13].

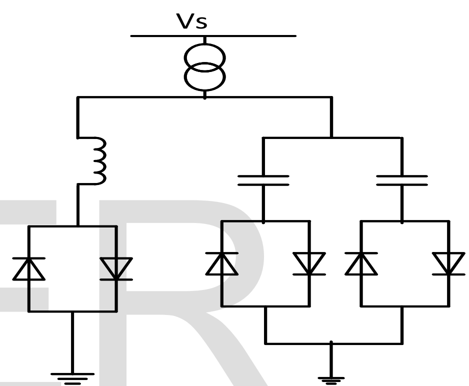

Fig. 1.Schematic diagram of SVC

3 HARMONY SEARCH ALGORITHMS

In the basic HS algorithm [14], [17], [18], [19] each solution is called a ‘‘harmony” and represented by an n-dimension real vector.

An initial population of harmony vectors is randomly generated and stored in a harmony memory (HM). Then a new candidate harmony is generated from all of the solutions in the HM by using a memory consideration rule, a pitch adjustment rule and a random re-initialization. Finally, the HM is updated by comparing the new candidate harmony and the worst harmony vector in the HM. The algorithm consists of three basic phases, namely, initialization, improvisation of a harmony vector and updating the HM.

Recently a GHS algorithm that modifies the pitch adjustment rule has been proposed [15]. Unlike the basic HS algorithm, the GHS algorithm generates a new harmony vector by making use of the best harmony vector in the HM.

In addition, the GHS algorithm employs the dynamic updating procedure for the PAR parameter. It is claimed that the modified pitch adjustment allows the GHS algorithm to

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work more efficiently on both continuous and discrete problems. An extension of the GHS algorithm, a self-adaptive GHS (SGHS) algorithm [9], [16], presented in this section employs a new improvisation scheme and an adaptive parameter tuning method. In this algorithm, four control parameters HMS (kept as a user defined value), HMCR, PAR and BW are closely related to the problem being solved and the phase of the search process that may be either exploration or exploitation.

1. Self-Adaptation of HMCR and PAR

HMCR is the probability of choosing one value from the historic values stored in HM. A large HMCR value favours local search thereby increasing the convergence rate of the algorithm, while a small HMCR value increases the diversity of the harmony memory. PAR is the adjustment rate for the pitch chosen from XB. A large PAR value favours passing the information of XB to next generation thereby enhancing the local exploitation ability of the algorithm around XB, whereas a small PAR value enables the new harmony vector to select its dimensions by perturbing the corresponding values in the harmony memory. Since local exploitation and global exploration are always entwined in the search process, it is difficult to fix the values for HMCR and PAR. After a specified number of learning period (LP) generations, HMCRm (PARm) is recalculated by averaging all the recorded HMCR (PAR) values during this period. With the new mean and the given standard deviation of 0.01 (0.05), new HMCR (PAR) value is produced and used in the subsequent iterations. As a result, an appropriate HMCR (PAR) value can be gradually learned to suit the particular problem and the particular phases of the search process.

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2. Dynamically changing BW

The parameter BW is a distance bandwidth for the continuous design variable. A large BW value favours the algorithm search in a large scope, while a small BW value is appropriate for fine-tuning of the best solution vectors. To well balance the exploration and exploitation of the proposed SGHS algorithm, the BW value decreases dynamically with increasing generations (NI). The SGHS algorithm does not require a precise setting of specific values to critical parameters HMCR, PAR and BW in accordance with the problem characteristic and complexity. These parameters are self-adapted by a learning mechanism or dynamically decreased with generation counter. Therefore, the SGHS algorithm can demonstrate consistently good performance on problems with different properties.

4. Case Studies

- System description

The single line diagram of the power system connected with wind farm is shown in Fig.(2). A 22 kV distribution system is fed by a 220 kV grid bus through a 220/22 kV, 47 MVA step down transformer. Two loads; first load of 5 MW, 0.96 p.f (lag) at the bus 1, second load 2 MW, 0.93 p.f (lag) at 25 km from bus 1 (at 50 km from first load). A 9 MW wind farm consisting of three 3 MW variable pitch wind turbines coupled with squirrel-cage induction generators is connected through step up transformer 0.575/22 kV, 4MVA to the 22 kV distribution network at 5 MW load bus. A fixed capacitor rated at 1.25 MVar is connected at the terminal of the IG.

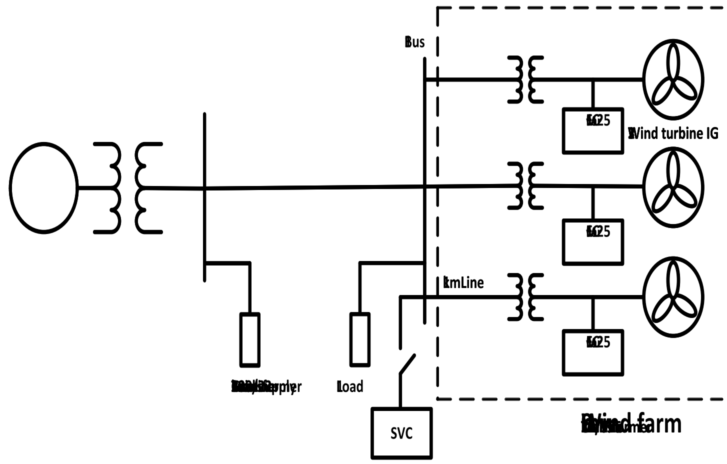
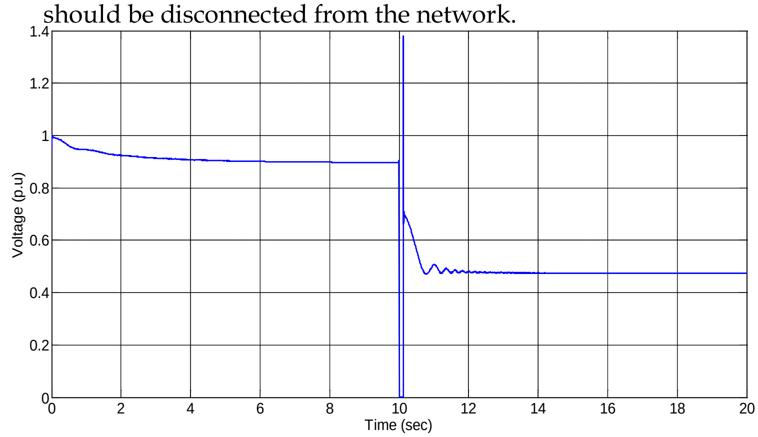


Fig. 2.Single line diagram of the power system connected with wind farm

Fault studies on this system

First, it will be connected without SVC. A solid three-phase-to-ground fault is initiated at Bus 1 connected to the bus wind farm and cleared by opening the breaker. The three-phase to ground fault was applied at 10s and cleared after 120ms. As shown in Fig. 3., during the fault, due to the reduction of the AC voltage, the generated active power and the electric torque are significantly reduced. This causes the rotor speed to increase. After the fault is cleared, As the reactive power supplied from fixed capacitor and network is insufficient to compensate reactive power absorbed during fault the terminal voltage is still low. Due to this, the generated electrical power is still less than the input mechanical power and hence, the rotor speed continue to rise. As the rotor slip is high, the generator absorbs large amount of reactive power from the network as clearly shown in Fig. 3(c). In this case the system becomes unstable and should be disconnected from the network.



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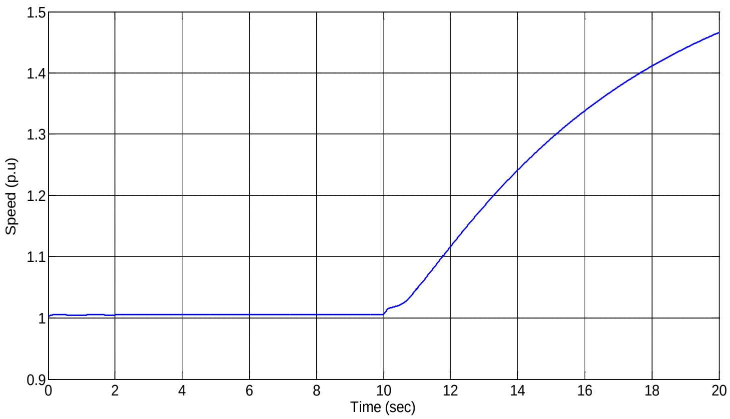

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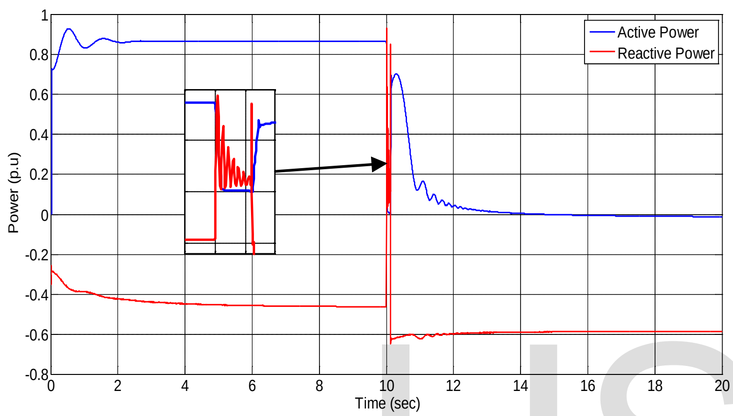

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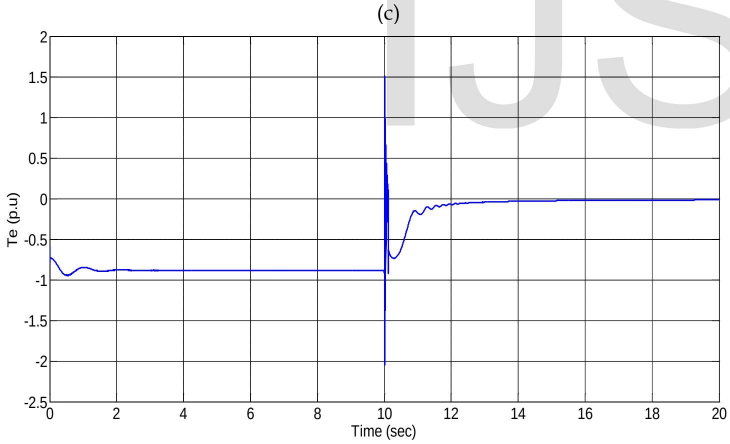
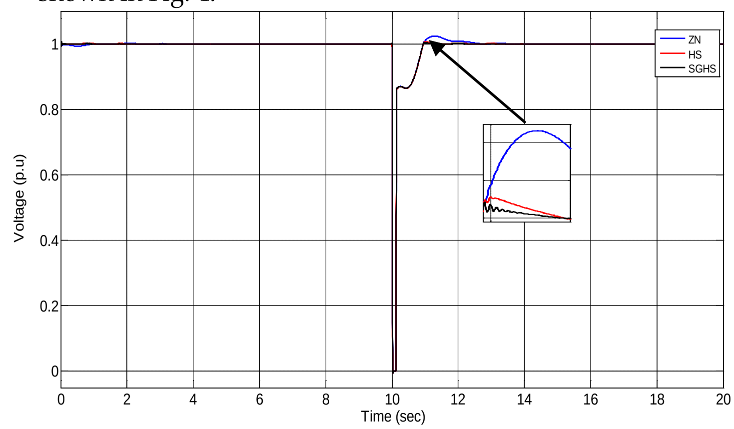


(d)

Fig.3 .

Fig. 3. Simulated results with PFC only (fault applied at 10s and lasted for 0.12s)
(a) Bus voltage. (b) Rotor speed.
(c) Active and Reactive power (d) Electric torque.

Second, it will be connected with svc and PI tuned by ZN HS, SGHS. Applying the previous symmetrical fault at 5 sec during the fault, the terminal voltage drops to zero and the machine currents increase substantially, then eventually decay to zero due to loss of an external excitation source. Due to the input mechanical power becomes more than the output electrical power (Pm>Pe), the rotor accelerates which can lead to instability. After the clearance of the fault the ac voltages recovers due to the reactive power supported from the SVC. The electric power now is higher than mechanical power (Pe>Pm) and the Kinetic energy stored during acceleration of rotor will be reduced. Eventually, the rotor slips back to its nominal value and also the AC voltage ,generator active power and reactive power absorption, as shown in Fig. 4.



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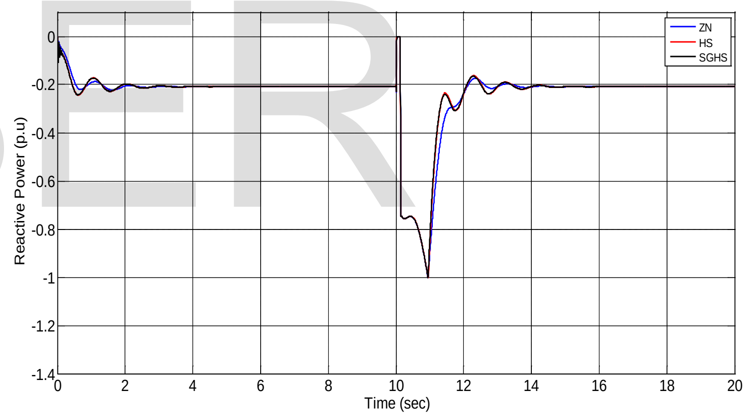

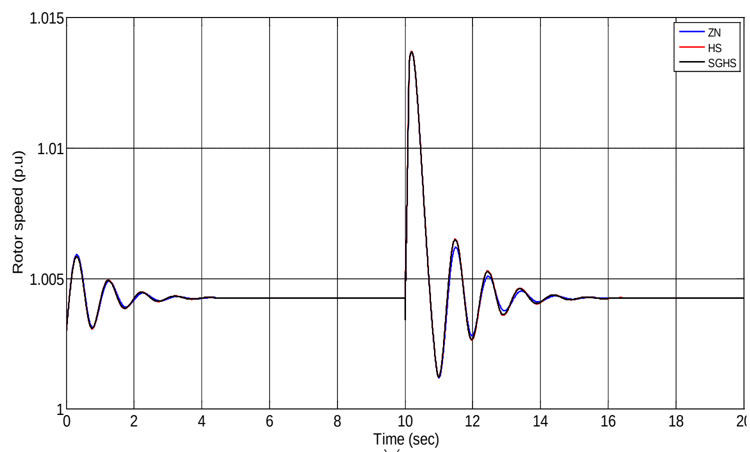

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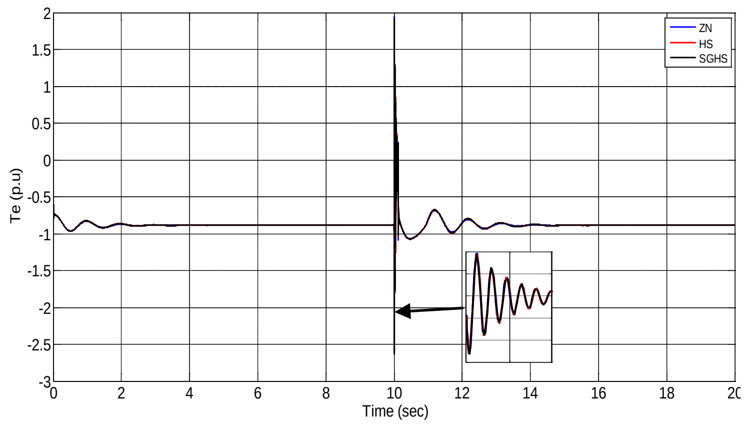

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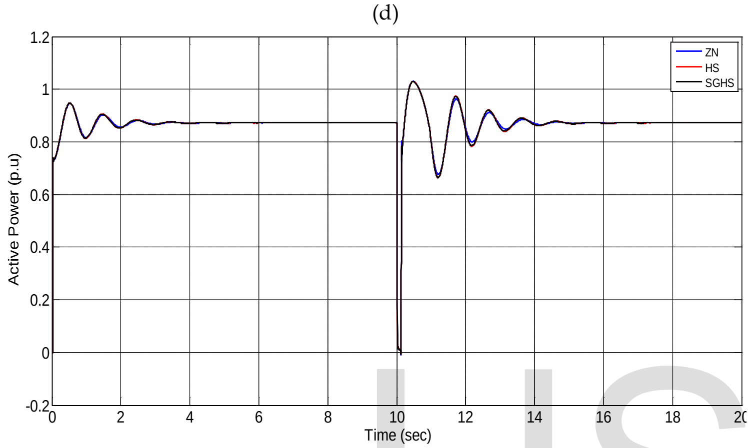

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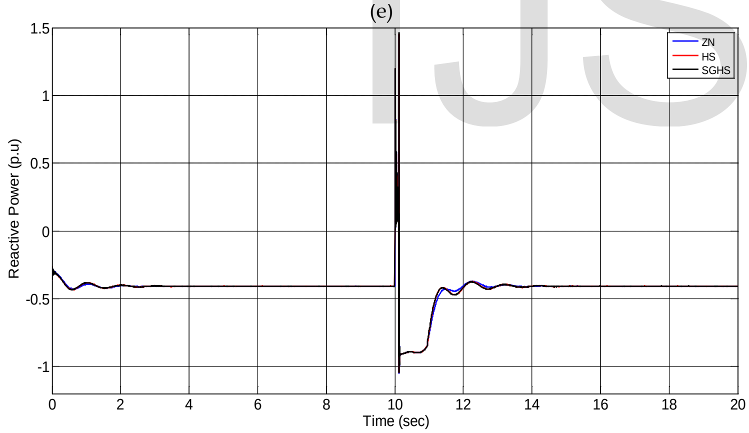


(f)

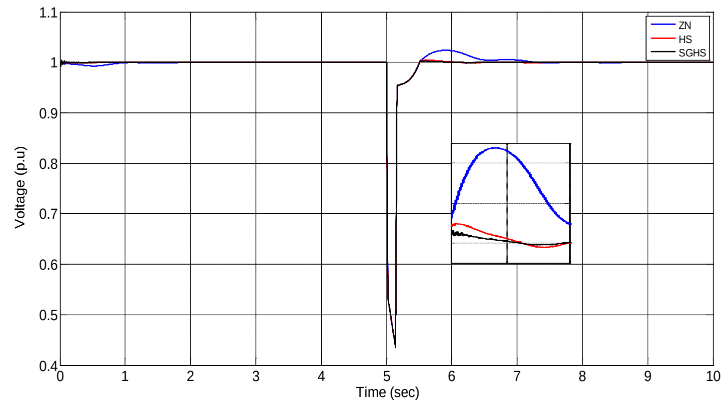
Fig. 4.

Fig. 4. Simulated results with SVC (fault applied at 10s and lasted for 0.12s)

(a) Bus voltage. (b) Reactive power supplied from SVC.
(c) Rotor speed. (d) Electric torque.
(e) Active power. (f) Reactive power absorbed by IG.

Terminal voltage profile of the system with SVC tuned by ZN, HS, SGHS.

Fig. 5. shows application of three phase to ground fault applied at 5sec at the end of transmission line (at bus 2)and cleared by opening the breaker after 140 ms.



(a)

Fig. 5.Voltage at bus1 under application of three phase to ground fault at the end of T.L for 140 ms (at bus 2)

Table. 1. Error, pos, and ts for application of fault at bus2 for SVC controller designed ZN,HS and SGHS

		KPSVC	KISVC	Error	POS (%)	Ts (s)
output voltage	ZN	14.144	42.4	.5551	56.38	7.5615
	HS	10.861	519.24	.4447	56.36	6.3489
	SGHS	11.745	1105.3	.4355	56.4	5.8576

Fig. 6. shows double line to ground fault is applied at 5sec at the end of transmission line (at bus 2)and cleared by opening the breaker after 140 ms.

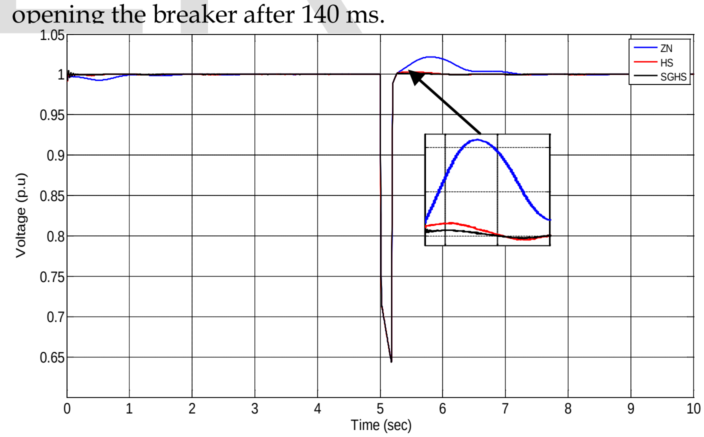


Fig. 6.Voltage at bus1 of the faulted phase under application of double line to ground fault at the middle of T.L for 180 ms (at bus 2)

Table. 2. Error, pos, and ts for application of fault at bus2 for SVC controller designed ZN,HS and SGHS

		KP_{SVC}	KI_{SVC}	Error	POS (%)	Ts (s)
output voltage	ZN	14.144	42.4	.4201	35.65	7.1597
	HS	10.861	519.24	.3128	35.65	5.9101
	SGHS	11.745	1105.3	.3053	35.65	5.7124

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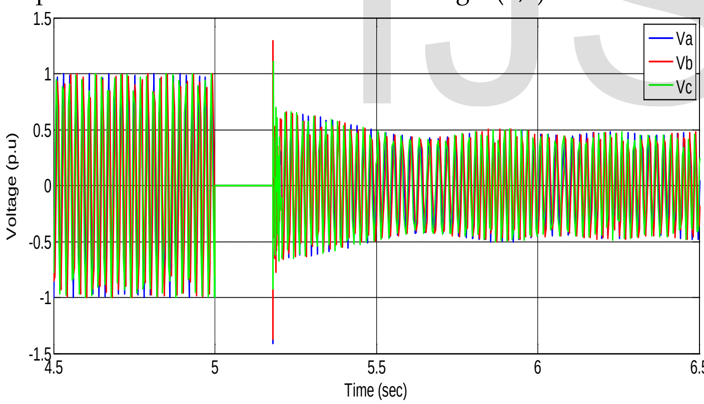
AS it is clear from Fig. (5,6). and table. (1,2)., after clearing fault the PI controller tuned by HS algorithms has the ability to return the terminal voltage to nominal value faster than HS and ZN controller. The SGHS showed slightly better performance than HS than HS in terms of error, settling time, percent of over shoot and hence, SVC with PI controller tuned by SGHS has better performance than HS and ZN.

Different types faults at different places will be studied on WECS with SVC tuned by SGHS.

First, as illustrated in Fig. 6. In case of symmetrical three phase to ground fault and double line to ground fault, The terminal voltage drops to zero and the machine currents increase substantially, then decay due to the loss of an external excitation source. The machine currents depending on the instant at which the fault occurs. Due to the input mechanical power becomes more than the output electrical power during the fault, the rotor accelerates. After clearance the fault, the voltage does not return quickly enough and hence the electric power is still less than the input mechanical power, the generator continues to accelerate. The system becomes unstable and must be disconnected from the network. The symmetrical fault is the most severe on the stability of system and imposes more heavy duty on the circuit breaker. The single line to ground fault doesn't effect on the stability of the system because during fault, the input mechanical power equals the output electrical power (balance) and the rotor speed remains constant as shown in Fig. 6(d,e).



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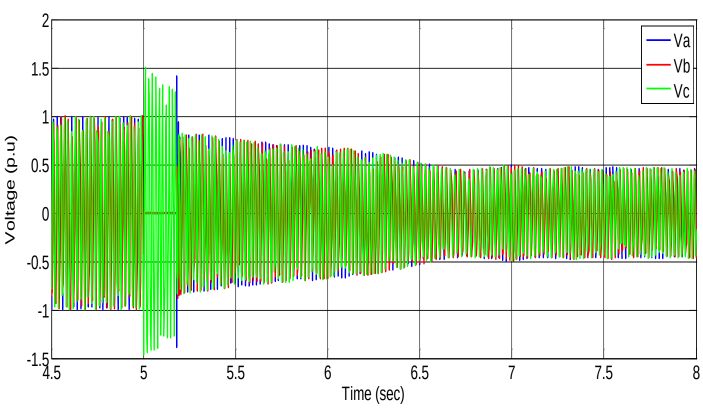

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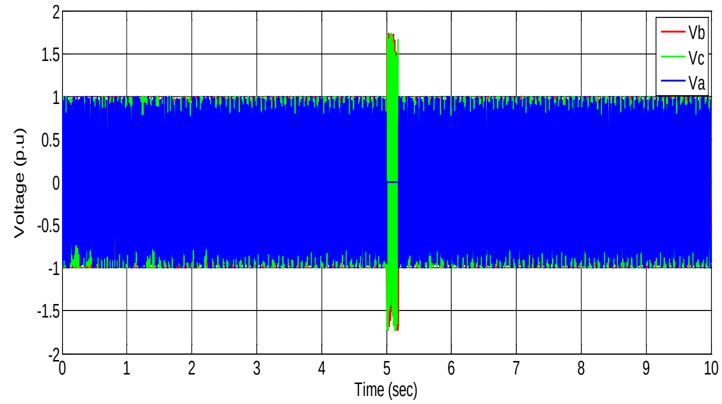

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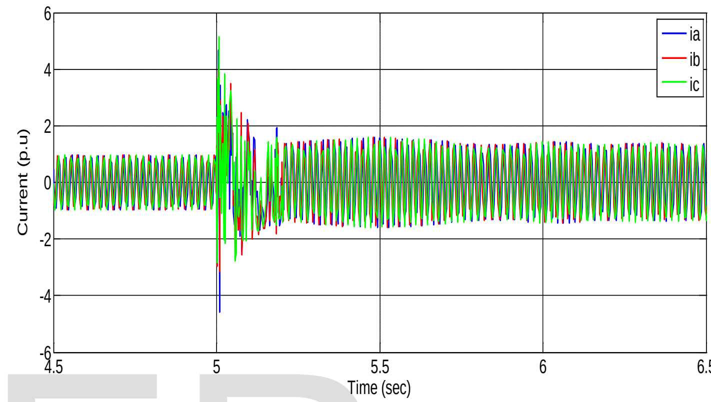

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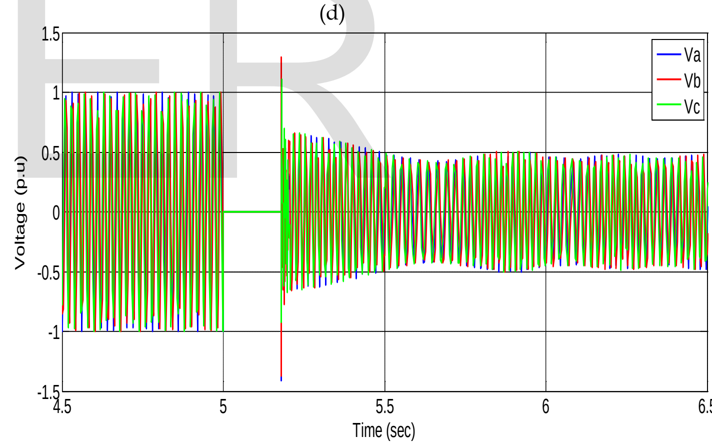

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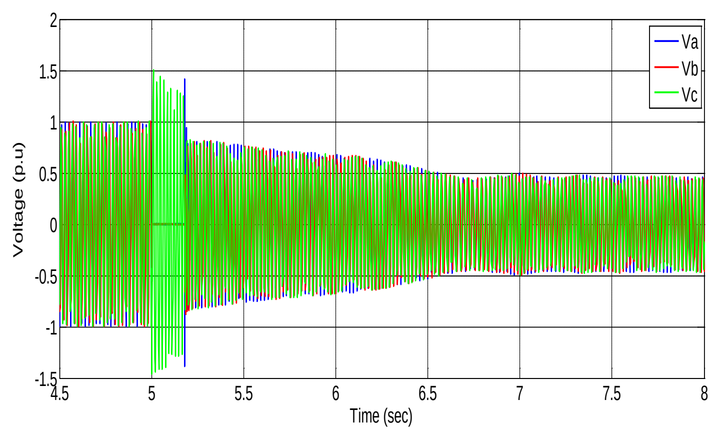

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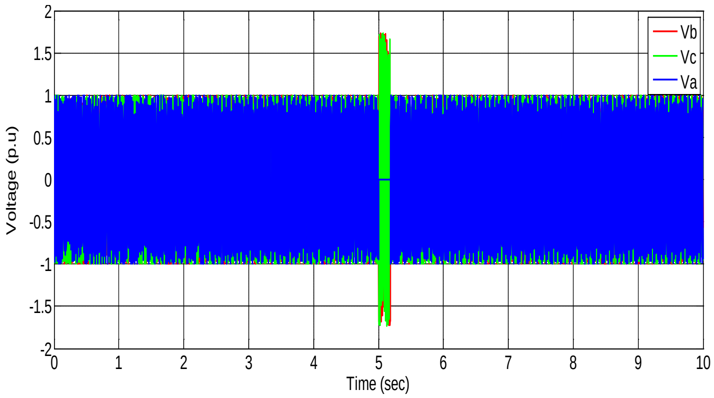

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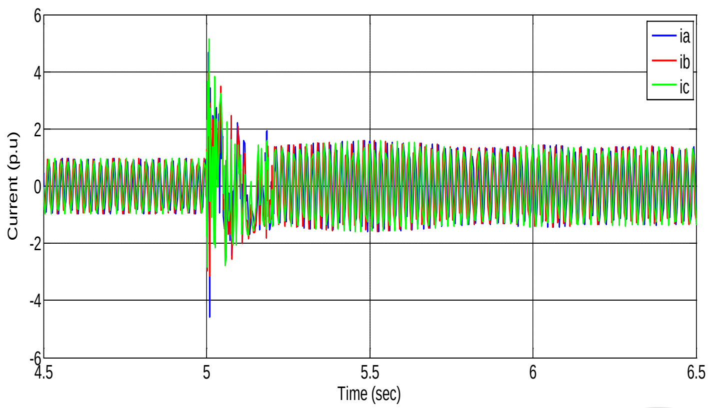

(h)

Fig.7 .

Fig. 7. Simulation results of the network with SVC tuned by SGHS (fault applied at 5s and lasted for 180ms)
(a) Bus voltage for 3-phase to ground fault.
(b) Bus voltage for 2-phase (A,B) to ground fault.
(c) Bus voltage for 1-phase (A) to ground fault.
(d) Active power from wind farm. (e) Rotor speed.

Second, Fig. 8. shows simulation results solid three-phase to ground fault applied at 5sec at the beginning, the middle and the end of transmission line (bus1) connected to the bus wind farm and cleared by opening the breaker after 120 ms.

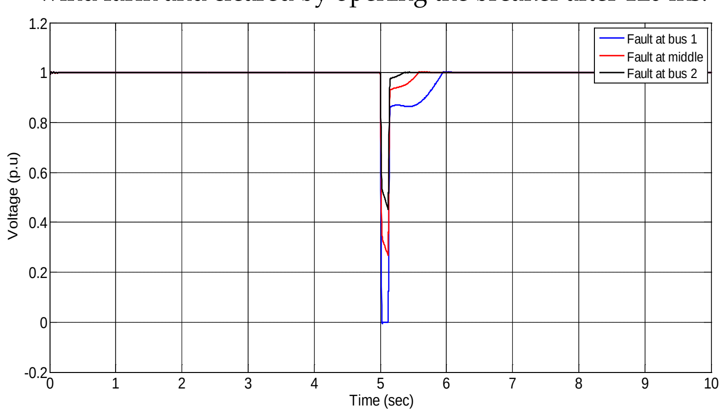

Fig. 8.Voltage at bus1 under application of 3-phase to ground fault at bus 1, middle of T.L and bus 2 for 120 ms

Fig. 9. shows simulation results for the same previous fault but lasted for 180 ms.

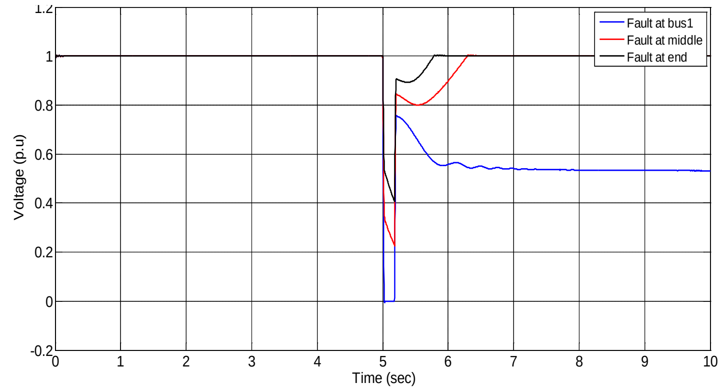

Fig. 9.Voltage at bus1 under application of 3-phase to ground fault at bus 1, middle of T.L and bus 2 for 180 ms

Fig. 10. shows simulation results for the same previous fault but lasted for 220 ms.

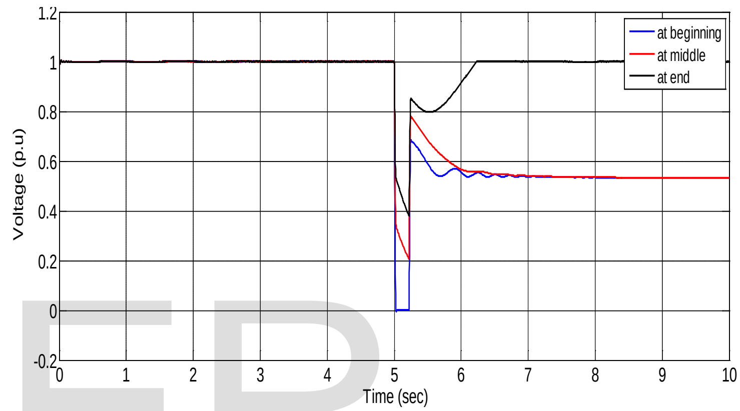

Fig. 10.Voltage at bus1 under application of 3-phase to ground fault at bus 1, middle of T.L and bus 2 for 220 ms

As it is clear from Fig. 8,9,10., when faults occur away from the IG terminals, the impedance between the machine and the fault increases and hence, the machine short circuit currents are not as high as in the case of a fault at the machine terminals. The machine terminal voltage does not immediately become zero after the fault, but decays with the machine current. Applied faults away from the IG increase the stability of system. As faults occur away from the IG, the stability of the system increases. Third, as shown in Fig. 11. increasing the period of the fault reduces the stability of the system.

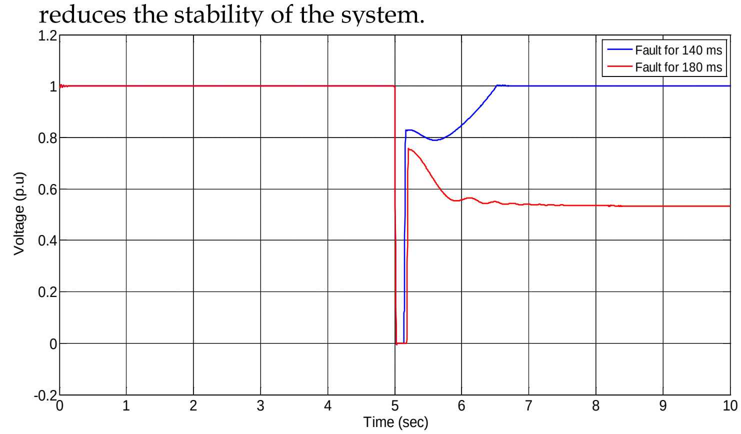

Fig. 11.Voltage at bus1 under application of 3-phase to ground fault at bus 1for 140 and 180 ms

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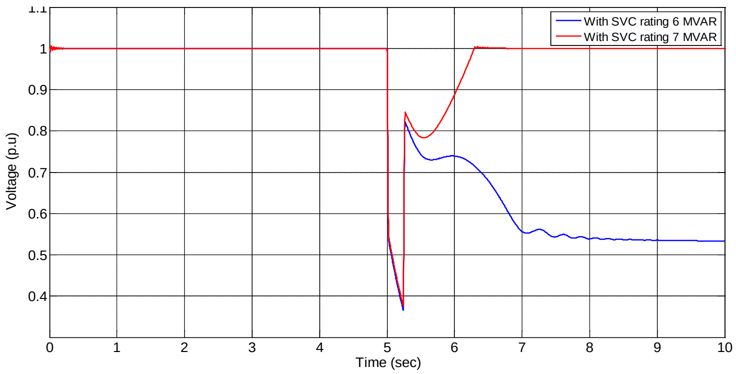
Forth, solid three-phase to ground fault applied at 5sec at the beginning of transmission line connected to the bus wind farm and cleared by opening the breaker after 240 ms. As shown in Fig. 12., the system is unstable.

with the same system configuration and an additional 1MVAR SVC, the AC voltage restores to the desired value after the clearance of the fault due to the extra reactive power support from the SVC.



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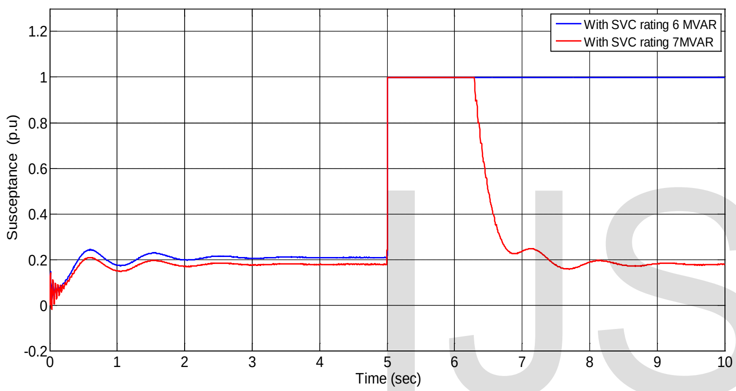

(b)

Fig. 12.

Fig. 12.simulated results under application of symmetrical 3-phase to ground fault at the end of T.L for 240 ms (a) Bus voltage. (b) susceptance of SVC.

5. Conclusion

The results show that, for symmetrical three phase fault and unsymmetrical faults, the SVC is effective in providing sufficient reactive power to the network after fault to compensate large reactive power absorbed from FSIG during fault and thus they considerably improve the system stability.

In this paper ZN,HS and SGHS algorithms have been presented to tune PI controller for SVC controller. The results show that, SGHS provides parameters with almost an optimal performance.

6. Appendix

Wind Turbine Induction Generator Parameters

Rated wind turbine mechanical output power: 3 MW
Rated wind speed: 9 m/s Rated line (Ph-Ph) voltage: 575 v Rated frequency: 50 Hz Rated power: 3.33333 MVA
Inertia constant: 5.04 s Friction factor: .01 p.u
Pole pairs: 3 Rs: 0.004843 Lls: 0.1248
Rr': 0.004377 Llr': 0.1791 Lm: 6.77 p.u

Transmission Line Parameters

Frequency: 50 R1: 0.1153 Ω/Km R0: 0.413 Ω/Km
L1: 1.05e-3 H/Km L0: 3.32e-3 H/Km
C1: 11.33e-009F/Km C0: 5.01e-009 F/Km
Line length: 50 km

SVC Parameters

System nominal voltage: 22000 v Frequency: 50 Hz
Power rating: 6 MVA
Reactive power limits
Qc: 6 MVAR Ql: -2.5 MVAR
Average time delay due to thyristor valves firing (Td): 4 ms

Transformer Parameters

Nominal Power: 47MVA Frequency: 50 Hz
Winding 1 Parameters
line voltage: 220 Kv R1: .00266 p.u L1: .08 p.u
Winding 2 Parameters
line voltage:22 Kv R2: .00266 p.u L2: .08 p.u
magnetizing resistance (Rm): 500 p.u
magnetizing inductance (Lm): 500 p.u

Grid Parameters

Line (Ph-Ph) Voltage (rms):220v Frequency:50Hz

Transformer Parameters

Nominal Power: 4MVA Frequency: 50 Hz
Winding 1 Parameters
line voltage: 22 Kv R1: .000833 p.u L1: .025 p.u
Winding 2 Parameters
line voltage:575v R2: .000833 p.u L2: .025 p.u
magnetizing resistance (Rm): 500 p.u
magnetizing inductance (Lm): 500 p.u

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