Stability Improvement of Isolated Wind-Diesel System with Optimized STATCOM Controller

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Abstract

Herein a reactive-power control scheme for an isolated wind-diesel hybrid generation with an induction generator (IG) for extraction of wind power and a synchronous generator (SG) for diesel-generator (DG) is presented. The reactive power consumed by IG and load is supplied by the Static Synchronous Compensator (STATCOM). Terminal voltage deviation is controlled by the STATCOM and thereby balances the reactive power. To optimize the PI controller adopted in the STATCOM, Teaching Learning Based Optimization (TLBO) and its modification: opposition based TLBO (OTLBO) has been used for minimizing integral time square error (ITSE). The mathematical model of the reactive-power-flow is presented. The parameters of the algorithm are set. The performance of OTLBO and TLBO is compared with Grey Wolf Optimizer (GWO), where OTLBO excels in all respect. The transient responses of the isolated system are also revealed for 1%, 5% and 20% step change in load reactive power for optimal STATCOM controller. The eigen-value analysis shows improvement in stability by the designed controllers. With the fitness function considered and rigorous optimization of the controller, the settling of the transient was possible within less than half of the time taken in earlier studies.

Keywords: SG, WG-DG, IG, STATCOM, TLBO, OTLBO, GWO

1. Introduction

Nowadays renewable power generation is increasing as it is eco-friendly, clean and sustainable as compared to generation from fossil fuels. But, for the irregular availability of wind and sun, they are hybridized with a diesel generator (DG) for reliable power supply to a small scale isolated system [1, 2]. The DG is of synchronous type. Asynchronous generation for varying wind speed, rugged construction and other advantages [3] make induction generator (IG) a suitable and cost-effective solution for it. But, the inducing flux is maintained by reactive power consumption. With the added demand for reactive power by IG, the generation faces mismatch. Thus, generator terminal voltage is more prone to fluctuation in such case and has detrimental effect on the supply quality and stability [4]. Hence, it is an important problem to be mitigated. Some solutions have been proposed in favour of the support from fixed capacitor bank for reactive power [5]. But, such demand of IG varies with load and wind, hence the fixed capacitors are the inadequate solution [6]. Alternatively, a family of Flexible AC transmission system (FACTS) devices [7] such as Switched Capacitor, Static VAR Compensator (SVC), [8, 9] Static Synchronous Compensator (STATCOM) can supply/absorb reactive power [10-21].

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For isolated applications, essentially an effective capacitive VAR controller is required for the WT-IG. Here, a STATCOM, [17] with a voltage source converter (VSC) fits and it smoothly produces inductive/capacitive reactive power with the bidirectional flow. After going through the above-referred works, it is observed that for proper control of the watt-less component in an isolated system, the controller are either proportional (P) or proportional plus integral (PI) type. If at all the controller is used, it is tuned by minimizing integral square of error (ISE) performance index on the deviation of voltage so that both positive or negative error can be reduced and thereby reducing overshoot or undershoot. But, it is noticed that the settling time of oscillations and steady-state error are high. Also, the tuning of the controller gains has been achieved by the conventional method. In [9] the PI controller gains for SVC and Automatic Voltage Regulator (AVR) have been optimized by Genetic Algorithm (GA). Optimization algorithms have imparted outstanding results with the help of computer program to attain optimal gains for controllers for stable operation in various fields of engineering. So there is scope for further improvement of STATCOM performance.

The integral time square error (ITSE) index is used in this work to optimally set controller gains as it also considers time. Hence it is effective in reducing settling time also [22]. To optimize, Teaching Learning Based Optimization (TLBO) has been used [23, 25]. The performance of TLBO was improved by introducing opposite population modifying it to Opposition based TLBO (OTLBO) whose improved performance is also presented in this problem. The performance of TLBO is judged side by side with Grey Wolf Optimizer (GWO), a recent one [24]. The parameters of the algorithms are first set in this context. The studied result of stability and transient responses of the isolated system are also revealed for 1%, 5% and 20% step change in load reactive demand for optimal STATCOM controller.

The mathematical model of the isolated system is depicted in Section 2. In Section 3 the features of TLBO and its modification is discussed. Section 4 embodies the results and responses of the system bringing out significant conclusions.

2. Mathematical Model of the System

The system under study has a DG, IG as wind generator (WG), consumer load and STATCOM as in Figure 1. First, the system state equations are obtained. The reactive power requirement in the system is assessed from terminal voltage deviation. The STATCOM is commanded by a Proportional-Integral (PI) controller as input to eradicate the reactive power difference. Also, the excitation system of the synchronous generator responds to voltage variation and helps to mitigate it.

The load asctive demand is met by the induction generator (IG) and synchronous generator (SG) in DG. The net reactive requirement for the operation of WG and load is supplemented by the DG and STATCOM.

The reactive power balance under steady state, [6]:

$$Q_{DG} + Q_{COM} = Q_{WG} + Q_L \quad (1)$$

where reactive powers in pu kVAR owe to that Q_{DG} , by SG in DG set; Q_{COM} , by STATCOM; Q_L , demand by the load (per unit kilovolt-amperes reactive); and Q_{WG} , by IG in wind generator. For the small signal analysis, let the small increment in reactive power load be ΔQ_L . By the action of the AVR and STATCOM, the reactive-power generation augments by an amount $\Delta Q_{DG} + \Delta Q_{COM}$. The mismatch in this watt-less demand equals $\Delta Q_{DG} + \Delta Q_{COM} - \Delta Q_{WG} - \Delta Q_L$. This will dually raise the terminal voltage:

- 1) by increasing the rate (d/dt) of electromagnetic-energy (E_{EM}) in the IG;

2) by a rise in reactive power input giving more voltage. The mathematical expression is

$$\Delta Q_{DG} + \Delta Q_{COM} - \Delta Q_{WG} - \Delta Q_L = d/dt(\Delta E_{EM}) + D_V \Delta V \quad (2)$$

Figure 1. The Isolated Wind-Diesel Hybrid Power Scheme

The electromagnetic energy accumulated in the WG is expressed by

$$E_{EM} = \frac{1}{2} L_M I_M^2 \quad (3)$$

The increment ΔE_{EM} can be written as

$$\Delta E_{EM} = E_{EM} - E_{EM}^0 = 2(E_{EM}^0/V^0)\Delta V \quad (4)$$

Where I_M , L_M , and X_M are the current drawn, inductance, and reactance of the IG, respectively.

Here V^0 and E_{EM}^0 quantify the terminal voltage and electromagnetic energy accumulated in the WG respectively in steady operating point.

Using (4), (2) can be written as

$$\Delta Q_{DG} + \Delta Q_{COM} - \Delta Q_{WG} - \Delta Q_L = 2(E_{EM}^0/V^0 Q_R) d/dt(\Delta V) + D_V \Delta V \quad (5)$$

E_{EM}^0/Q_R is given by

$$E_{EM}^0/Q_R = 1/(4\pi f K_R) = H_R \quad (6)$$

where H_R represents the system inertia, f is the frequency of emf generated and K_R equals to system reactive-power rating divided by the rated magnetizing reactive power of WG. Substituting from (6) in (5), and taking Laplace transform, it is rewritten as

$$\Delta V(s) = K_V/(1 + s T_V) [\Delta Q_{DG} + \Delta Q_{COM} - \Delta Q_{WG} - \Delta Q_L] \quad (7)$$

where

$$T_V = 2H_R/D_V V^0 \quad \text{and} \quad K_V = 1/D_V.$$

In Laplace transform, $\Delta Q_{DG}(s)$ can be written as

$$\Delta Q_{DG}(s) = K_3 \Delta E'_q(s) + K_4 \Delta V(s). \quad (8)$$

Where in

$$K_3 = (V \cos \delta) / X'_d \text{ and } K_4 = (E'_q \cos \delta - 2V) / X'_d.$$

Also

$$E'_q(s) = 1/(1 + sT_G)[K_1 \Delta E_{fd}(s) + K_2 \Delta V(s)] \quad (9)$$

where

$$T_G = X'_d T'_{d0} / X_d; K_1 = X'_d / X_d \text{ and } K_2 = (X_d - X'_d) \cos \delta / X_d.$$

Here, ΔE_{fd} and $\Delta E'_q$ are the small variation in the field voltage and armature in q axis under transient conditions, respectively. T'_{d0} is the d axis open-circuit transient time constant. δ is the power angle. X_d and X'_d are d axis reactance of synchronous generator under steady-state and transient conditions, respectively.

Similarly, for constant slip, derived from machine model [13]:

$$\Delta Q_{WG}(s) = K_5 \Delta V(s) \quad (10)$$

Where,

$$K_5 = 2V X_{eq} / (R_Y^2 + X_{eq}^2); R_Y = R_p - R_{eq} \text{ and } R_p = (R_2/s) - 1.$$

The STATCOM can produce or take in reactive power by proper firing angle α of the inverter and maintain the desired terminal voltage of the interconnection [17]. So

$$\Delta Q_{COM} = f(\alpha, V) \quad (11)$$

The linearized STATCOM model is stated as:

$$\Delta Q_{COM} = \frac{\partial Q}{\partial \alpha} \Delta \alpha + \frac{\partial Q}{\partial V} \Delta V \quad (12)$$

$$\Delta Q_{COM}(s) = K_7 \Delta \alpha(s) + K_6 \Delta V(s) \quad (13)$$

Where

$$\Delta \alpha = (K_p + K_i/s) \Delta V$$

Wherein, K_p and K_i are respective gains of the PI controller in the STATCOM controller.

The developed transfer function model is shown in Figure 2. The fitness function taken is ITSE as it gives the better reduction of overshoot and settling time.

Fitness function

$$J = \int_T^{T_{sim}} \Delta V^2 dt \quad (14)$$

Where T_{sim} is the simulation run time.

The problem of STATCOM controller optimization presented here is an offline optimization taken up by OTLBO.

Figure 2. Transfer Function Model of the Scheme

3. Oppositional Teaching-Learning-Based Optimization (OTLBO) Algorithm

In a classroom, each individual learns not only from the teacher but also from the fellow learners to get the best grades. Based on this, the TLBO algorithm has two main parts of learning: (i) From the teacher (named the teacher phase) and (ii) From other students (named the learner phase). TLBO takes a population of students (*i.e.*, learner) for whom the different subjects are the variables to optimize. The net grade of the student is analogous to the objective function. The best student as per fitness/objective function is taken as a teacher.

Teaching Part

In this part, a teacher teaches the students and improves the average performance of the class. For a 'm' dimensional problem with population size 'n' number of learners ($k = 1, 2, \dots, n$). At a step, i , of the cycle $M_{j,i}$ is the mean performance of the students in a specific subject 'j' ($j = 1, 2, \dots, m$). Denoting $X_{total-kbest,i}$ as the best result or teacher taking all the subjects, due to the diversity of students, the students' results deviate from that of teacher and the mean in each subject *i.e.*,

$$Difference\_mean = r_i (X_{j,k,besti} - T_f M_{i,j}) \quad (15)$$

Where the teaching factor

$$T_f = round[1 + r_f \{2 - 1\}] \quad (16)$$

and $X_{j,k,besti}$ is the best grade (teacher) in subject j. r_i and r_f are randomly generated in [0, 1]. The feature T_f need not be adjusted as a parameter but it maintains search diversity. The existing performance is improved in teacher phase as per the equation:

$$X'_{j,k,i} = X_{j,k,i} + Difference\_mean_{j,i} \quad (17)$$

If $X'_{j,k,i}$ has a better result, then it is selected as per the fitness function evaluation. On completion of the teacher phase, the selected function values enter the learner phase. In TLBO only population size and the number of generations are tuned not r_i , r_f and T_f . Thus, it is easy to implement the algorithm for a problem which reduces the time for setting control parameters.

Figure 3. Flowchart for OTLBO Algorithm

Learning Part

Besides teaching, the students acquire knowledge by the cooperative discussion with classmates. An inferior learner learns from superior one who acquired more knowledge. The learning process is stated as below. After teacher phase, selecting two learners, A and B, such that $X'_{total-j,A,i} \neq X'_{total-j,B,i}$ and student A updates to $X''_{j,P,l}$ as below:

$$X''_{j.Ai} = X'_{j.Ai} + r_i(X'_{j.Ai} - X'_{j.Bi}), \text{ If } X'_{j.Ai} < X'_{j.Bi}, \quad (18a)$$

$$X''_{j.Ai} = X'_{j.Ai} + r_i(X'_{j.Bi} - X'_{j.Ai}), \text{ If } X'_{j.Bi} < X'_{j.Ai} \quad (18b)$$

In a similar manner to teaching part $X''_{j.Pi}$ is allowed if it is a superior one.

Opposition Population

The opposition population is generated in OTLBO for better convergence result from normal class $X[x_{i,1}, x_{i,2}, \dots, x_{i,n}]$ with bounds $[lb_j, ub_j]$ for $j=1 \dots n$ as

$$x_{i,j}^o = lb_j + ub_j - x_{i,j} \quad (19)$$

In both teaching and learning part, the opposite population is evaluated and updated in a similar way as above and better solution of the total population is considered. The flow of the algorithm can be clearly understood from Figure 3.

4. Simulation Results

The mathematical model depicted in Section 3 is built in MATLAB Simulink with parameters in Appendix A [8,15]. The transients are assessed in the time domain and compared to determine K_p and K_i .

4.1. Optimization of K_p and K_i

The model is simulated for 1% step change of load and the following K_p , K_i , ΔV , settling time, overshoot, undershoot and the fitness function ITSE's lowest value are taken. The set of the values for K_p and K_i that minimize the fitness function is selected. Three optimizations namely, OTLBO, TLBO and GWO are compared here. The model is simulated in MATLAB SIMULINK 7.9 run in Intel i5 with 8 GB RAM.

First, TLBO is selected as the optimization algorithm and the parameters are set. Three sets of population size and iteration are taken. For each set of population size and iteration, the algorithm is run 20 times and best cases are shown for comparison of performance as tabulated in Table 1. It can be seen that increase in iterations increases accuracy.

Table 1. Parameter Variation Effect of TLBO

Sl. No.	No of populati	Iteration	K_p	K_i	ΔV	J=ITSE	Settling time (s)	Over-shoot	Under-shoot
1	30	40	20.72 27121 28846 627	9386. 08518 43890 54	4.12396 923418 917 $\times 10^{-11}$	2.20944 350792 479 $\times 10^{-14}$	4.65135 276611 9749 $\times 10^{-11}$	1.21128 392529 3932 $\times 10^{-4}$	- 7.602689511 157098 $\times 10^{-4}$
2	30	50	20.72 27125 09795 823	9386. 08606 81693 03	4.12396 836511 267 $\times 10^{-11}$	2.20944 350792 481 $\times 10^{-14}$	4.65135 189101 1103 $\times 10^{-11}$	1.21128 403171 550 $\times 10^{-4}$	- 7.602689508 792526 $\times 10^{-4}$
3	30	60	20.72 27133 00350 055	9386. 08544 11038 30	4.12396 905363 152 $\times 10^{-11}$	2.20944 350792 479 $\times 10^{-14}$	4.65135 262553 6452 $\times 10^{-11}$	1.21128 402447 8502 $\times 10^{-4}$	- 7.602689504 104288 $\times 10^{-4}$

Table 2. Parameter Variation Effect of OTLBO

Sl. No.	No of population	Iteration	K_p	K_i	ΔV	J=ITSE	Settling time (s)	Over-shoot	Under-shoot
1	30	40	21.52 95872 53715 7	9754. 55492 89053 8	3.81767 787909 989X10 ⁻¹¹	2.04172 472204 9410X10 ⁻¹⁴	4.3059 X10 ⁻¹¹	1.16723 431744 698 X10 ⁻⁴	- 7.343777103 44419 X10 ⁻⁴
2	30	50	21.52 95873 89829 5	9754. 55527 70864 5	3.81767 758331 788 X10 ⁻¹¹	2.04172 472204 9421 X10 ⁻¹⁴	4.3059 X10 ⁻¹¹	1.16723 435547 645 X10 ⁻⁴	- 7.343777102 70677 X10 ⁻⁴
3	30	60	21.52 95872 53715 7	9754. 55492 89053 8	3.81767 787909 989 X10 ⁻¹¹	2.04172 472204 9410 X10 ⁻¹⁴	4.3059 X10 ⁻¹¹	1.16723 431744 698 X10 ⁻⁴	- 7.343777103 44419 X10 ⁻⁴

From Table 1 it is observed that the least value of ITSE comes for K_p =20.722713300350055 and K_i =9386.085441103830. The best results are obtained for population size 30 run for 60 iterations. From Table 2 it is observed that minimum of ITSE is the same for all the three cases of varying number of iterations for OTLBO. It indicates the consistency of the algorithm and brings up the fact that 40 runs are sufficient with OTLBO to get the convergent result, which is an improvement on TLBO. Comparing ITSE in Table 1 and Table 2, OTLBO has significantly minimized ITSE as compared to TLBO and that also reflects in the reduction of overshoot, undershoot, settling time and steady-state value of ΔV . For comparison, GWO is selected as this algorithm is also parameter-free [24]. In a similar manner, the performance of GWO is quantified in Table 3.

Table 3. Parameter Variation Effect of GWO

Sl. No.	No of population	Iteration	K_p	K_i	ΔV	ITSE	Settling time (s)	Over-shoot	Under-shoot
1	30	40	20.73 8529	9427. 5933	4.083134 9586255 8X10 ⁻¹¹	2.2094791 6022499 X10 ⁻¹⁴	4.6057328 27171594 X10 ⁻¹¹	1.2161 X10 ⁻⁴	-7.6026 X10 ⁻⁴
2	30	50	20.74 7339	9395. 3286	4.116356 1835003 6 X10 ⁻¹¹	2.2094518 4707280 X10 ⁻¹⁴	4.6427179 42636307 X10 ⁻¹¹	1.2137 X10 ⁻⁴	-7.6026 X10 ⁻⁴
3	30	60	20.72 4951	9399. 7491	4.110244 6003106 4 X10 ⁻¹¹	2.2094474 9179710 X10 ⁻¹⁴	4.6360386 36632027 X10 ⁻¹¹	1.2127 X10 ⁻⁴	-7.6027 X10 ⁻⁴

From the above table, it is observed that the least value of ITSE comes for K_p = 20.724951 and K_i =9399.7491 for population size 30 run for 60 iterations.

Overall, comparing the best ITSE values for all the three the order from best to worst is OTLBO, TLBO and GWO. The convergence of objective function *i. e.*, cost plotted for best cases of GWO and OTLBO algorithms taken are compared in Figure 4.

Figure 4. Convergence Plot

Here it is observed that the OTLBO converges faster and more accurately than GWO. It can also be seen that OTLBO has started with good function value and reached the best in seven iterations, TLBO has also reached the best value around seven iterations though not shown here. This gives an indication that fewer iterations of OTLBO can save time without loss of accuracy. But, the best controller gains obtained in all the three algorithms for the third row in the respective table is considered for future simulations in controlling the STATCOM for a consistent comparison.

4.2. Comparison of Results with and Without STATCOM

The deviations in bus voltage ΔV , the reactive powers: supplied by SG, ΔQ_{DG} ,

Fig. 5(a)

Fig. 5(b)

Fig. 5(c)

Fig. 5(d)

Figure 5. Transient Responses of System Showing (a) ΔV (b) ΔQ_{DG} (c) ΔQ_{WG} (d) ΔQ_{COM} with 1% Load

consumed by IG, ΔQ_{WG} and generated by STATCOM, ΔQ_{COM} are presented in Figure 5 (a), (b), (c) and (d) respectively for 1% load change with and without STATCOM.

It is observed that at an instant increase of load the terminal voltage reduced. This resulted in raising the supply of ΔQ_{DG} and ΔQ_{COM} . The ΔQ_{DG} decreases as ΔV reduces.

The reactive power needed by the load eventually shifts to STATCOM when steady state is reached. In earlier works for the similar rating of system optimized using ISE criteria only the improvement in overshoot and undershoot have been reported [10-18]. But, it can be seen that the overshoot in ΔV was mostly in the range of 4×10^{-4} and it was highly oscillatory response taking too long to settle around 7 cycles [16]. When optimized with the ITSE criteria the transients settle in 5 cycles. The optimal STATCOM controller designed here accurately settles the ΔV following disturbance to nearly zero compared to a case where no reactive power support is given [4]. Thus a faster control is achieved.

4.3. Transient Responses for Various Load Conditions

The model is run for various reactive load conditions and the respective dynamic performances are observed. The eigen-values are also found out for different controllers

Table 4. Effect on eigen-values by Controllers

No STATCOM	GWO-STATCOM	TLBO-STATCOM	OTLBO-STATCOM
-0.0600X10⁻⁴	-8.3867 X10⁻⁴	-8.3867 X10⁻⁴	-8.3878X10⁻⁴
-0.5000 X10 ⁻⁴	(-0.2427 + 0.4342i) X10 ⁻⁴	(-0.2427 + 0.4342i) X10 ⁻⁴	(-0.2421 + 0.4451i) X10 ⁻⁴
0 X10 ⁻⁴	(-0.2427 - 0.4342i) X10 ⁻⁴	(-0.2427 - 0.4342i) X10 ⁻⁴	(-0.2421 - 0.4451i) X10 ⁻⁴
-5.9443 X10 ⁻⁴	-0.0440 X10 ⁻⁴	-0.0440 X10 ⁻⁴	-0.0440 X10 ⁻⁴
(-0.0011 + 0.0031i) X10 ⁻⁴	(-0.0012 + 0.0031i) X10 ⁻⁴	(-0.0012 + 0.0031i) X10 ⁻⁴	(-0.0012 + 0.0031i) X10 ⁻⁴
(-0.0011 - 0.0031i) X10 ⁻⁴	(-0.0012 - 0.0031i) X10 ⁻⁴	(-0.0012 - 0.0031i) X10 ⁻⁴	(-0.0012 - 0.0031i) X10 ⁻⁴
(-0.0000 + 0.0000i) X10 ⁻⁴	-0.0000 X10 ⁻⁴	-0.0000 X10 ⁻⁴	-0.0000 X10 ⁻⁴
(-0.0000 - 0.0000i) X10 ⁻⁴	-0.0001 X10 ⁻⁴	-0.0001 X10 ⁻⁴	-0.0001 X10 ⁻⁴

and tabulated in Table 4. Significant damping has been introduced in dominant eigen-value (shown in bold) by proper design of STATCOM controller by OTLBO and stability is improved.

It is observed from Figure 6(a)-(d), that the reactive power consumption increases with increase in load. This power is initially met by the synchronous generator. The reactive demand of 20% is finally met by the STATCOM, ΔQ_{COM} . At first the SG meets the demand raising ΔQ_{DG} ; later on, the designed PI controller for STATCOM brings down the error in ΔV and settles ΔQ_{WG} . The settling time is more or less unaffected for the controller but the overshoot has slightly increased. However, 20% increase in reactive power demand is too high and seldom occurs; the performance sensitivity in small variation up to 5% is less. When the disturbance occurs, ΔQ_{WG} also increases. The transient dies out within three cycles.

Figure 6. Transient Responses of System Showing (a) ΔV (b) ΔQ_{DG} (c) ΔQ_{WG} (d) ΔQ_{COM} with Time for Various Load Conditions

5. Conclusion

The reactive power control of an isolated wind-diesel hybrid generation has been discussed. An IG generates power from wind with DG and STATCOM support in the system. The dynamics of load variation in the system is examined after optimizing the controller gains of the STATCOM using OTLBO, TLBO optimization algorithm and compared with GWO algorithm. The effect of the change in load on the dynamic performance is studied with three incremental load conditions. The least number of the control parameter of all the three algorithms reduced a significant time taken for parameter adjustment. In the process of optimization, the accuracy of OTLBO is far better as compared to the rest two. The STATCOM helps the transients caused by load disturbances to die out effectively within 0.01s once the controller parameters are optimized offline. The STATCOM takes up to support the reactive power demand and steady state is attained. In future, advanced control and optimization methods can be deployed for improvement of the dynamics of isolated wind-diesel generation for larger variation and variety of load. Multiple hybrid generation systems with enhanced capacity can be studied in such aspect for benefit of isolated consumer load, instead of grid connection.

APPENDIX A: System Parameters [8,15]

SYSTEM LOAD	Value	Constants	Values
WIND CAPACITY(kW)	150	K_A	40
DIESEL CAPACITY(kW)	150	$T_{A,S}$	0.05
LOAD CAPACITY(kW)	250	K_f	0.5
$P_{SG,pu}$ Kw	0.4	$T_{f,S}$	0.715
$Q_{DG,pu}$ Kvar	0.2	K_E	1.0
E_q,pu	1.1136	$S_{F,S}$	0.0
$\delta,^\circ$	21.05	$T_{E,S}$	0.55
E_q',pu	0.9603	$T_{a,S}$	0.005

V, pu	1.0	$T_{d,s}$	0.001667
X_d, pu	1.0	K_1	0.15
X_d', pu	0.15	K_2	0.793232
$T'_{do,s}$	5.0	K_3	6.22143
$P_{IG}, \text{pu Kw}$	0.6	K_4	-7.358895
$Q_{WG}, \text{pu kVAR}$	0.189	K_5	0.126043
$P_{in}, \text{pu kW}$	0.75	K_6	1.478
$\eta_{IG}, \%$	80	K_7	1.0
$r_1=r_2, \text{pu}$	0.19	K_v	0.6667
$x_1=x_2, \text{pu}$	0.56	K_α	0.446423
$s, \%$	-4.1	T_v	0.000106
$P_L, \text{pu kW}$	1.0		
$Q_L, \text{pu kVAR}$	0.75		
pf (lagging)	0.8		
$Q_{COM}=Q_{WG}+Q_L-Q_{DG}, \text{pu kVAR}$	0.739		
$Q_c, \text{pu kVAR}$	0.85		
$\alpha, \text{radians}$	2.443985		

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