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# MODIFIED GWO UPDATING PARAMETER FOR TUNING OF PITCH CONTROL OF FIXED SPEED WIND TURBINE

**Aliyu Hamza Sule**

*Department of Electrical Engineering,*
*Hassan Usman Katsina Polytechnic, P.M.B. 2052, Katsina, Katsina State, Nigeria*

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**Abstract -** *The Proportional and Integral (PI) controller found in the pitch control of the Wind Turbine has to be tuned to improve the pitch control performance. In this study, the updating parameter of the Grey Wolf Optimizer (GWO) was modified and the modified GWO was applied to tune the gains of the controller for improving the pitch control tuning results. The controller tuning is formulated as the minimization of the Integral Time multiplied Square Error (ITSE) objective function under controller gains constraints. The modified GWO tuning results were validated through a comparison of its tuning results with that of GWO. The modified GWO exhibited faster convergence speed and provided better-tuned PI gains of the controller than the GWO. The faster settling time in pitch control of the Wind Turbine provided by the modified GWO can reduce the stress in the pitch control of the Wind Turbine compared to GWO.*

***Key Words***: Modified Grey Wolf Optimizer, updating parameter, tuning of pitch control, fixed speed wind turbine.

## 1. INTRODUCTION

The Grey Wolf Optimizer (GWO) is one of the population-based algorithms which was developed by Mir Jalili [1]. It mimics the leadership hierarchy and hunting strategy of grey wolves as one of the top predators in the food chain. The GWO apply its exploration and exploitation capabilities to find the optimal solution to a tuning problem. At the top of the hierarchy of the wolves is the α wolf which is the fittest wolf in the pack normally consisting of 5 or 12 wolves. And next to the α wolf in the leadership hierarchy is the β wolves which assist the α wolf. The δ wolves are the third in the leadership hierarchy, and they shoulder more responsibility for searching for prey and encouraging the rest of the wolves to follow the α wolf. The lowest in the leadership hierarchy are the ω wolves. Their movements depend on how they are instructed by the wolves above them in the leadership [2]. One of the advantages of GWO is its simplicity. It only requires adjusting two parameters to overcome its near-optimal convergence problem and sharing knowledge of the search space between its search agents. Also, adapting the values of vector A and operator a, ensures the efficient transition of its exploration and exploitation behaviour [1]. However, the GWO has some limitations such as low accuracy and slow convergence speed [3] these led researchers to conduct many studies to improve its performance.

The accuracy and convergence speed of GWO was improved by [3] through the hybridization of GWO with the Modified Differential Evolution (MDE) algorithm to form MDE-GWO. This improved the GWO search ability and local optimum avoidance. The influence of dominant wolves in improving the searching ability of the GWO was studied in [4], where the dominant wolves were varied at the commencement of every iteration. Furthermore, the dominant wolves were guided by learning data in establishing the three dominant wolves in the subsequent generations. These modifications of the GWO improved its performance in solving optimization problems more than the standard GWO. The a and A parameters of a GWO were tuned in [5] to form the modified GWO. This led to the proper balance between its exploration and exploitation stages, consequently, the modified GWO to converged faster than the GWO. The authors [6] improved the capability of the fittest wolves in the pact to occupy better positions during iterations. This is achieved by balancing the exploitation and exploration stages of the GWO. The simulation result shows improved performance of AGC tuned with the Modified GWO compare with the untuned AGC. The Lévy flight and greedy selection processes were embedded in the GWO [7] to modify its hunting stages This solves the problem of insuffient diversity of wolves in the GWO.

The limitation of assigning alpha, beta and delta wolves with the same leadership superiority in the GWO updating position mechanism which contradicts the social leadership of the wolves was solved in [3] through hybridization of the GWO with Modified Differential Evolution to form MDE-GWO. It is observed in this study the updating mechanism of the GWO, where the best positions of Alpha (λ), Beta (β) and Delta (δ) wolves used to update the positions of the ω wolves, the three best wolves have equal influences in the updating mechanism. The equal influence has violated the social hierarchy of the wolves and the violation has the possibility of not providing an optimal updating mechanism. The objectives of this study are:

1) To modify the updating parameter of the GWO
2) To Formulate the transfer function of the closed-loop pitch control system of fixed-speed Wind Turbine.

3) To develop the ITSE objective function for PI controller tuning in the pitch control of the fixed-speed Wind Turbine.

. The contribution of this study is the modification of updating parameter of the GWO, which models the updating of wolves' positions from the best positions of α, β and δ wolves, and this enhanced the average convergence speed of the GWO. Furthermore, the modification of the GWO updating parameter provided better-tuned gains of the PI controller in the pitch control of the Wind Turbine compared to GWO. The structure of this paper consists of the introduction, principle of operation of grey wolf optimizer, methodology, results and discussion, conclusion, Acknowledgement and list of references.

## PRINCIPLES OF OPERATION OF GREY WOLF OPTIMIZER

The operation of GWO involved scouting, encircling and attacking prey by wolves are described in this section.

### Hunting the prey

While hunting, the grey wolves identified the position of the prey and enclosed it. The locations in the search space for the best three solutions to $K_p$ and $K_i$ gains of the PI controller correspond to α, β and δ wolves. Their positions relative to the prey position are presented in Equations (1) - (3). Equations (4) - (6) modelled the best positions of $\alpha$ $\beta$ and $\delta$ wolves from the prey, while Equation (7) represents the updating of positions of wolves from the positions of $\alpha$ $\beta$ and $\delta$ wolves [8], [9]

$$\vec{D}_\alpha = |\vec{C}_1\vec{X}_\alpha - \vec{X}| \quad (1)$$

$$\vec{D}_\beta = |\vec{C}_2\vec{X}_\beta - \vec{X}| \quad (2)$$

$$\vec{D}_\delta = |\vec{C}_3\vec{X}_\delta - \vec{X}| \quad (3)$$

$$\vec{X}_1 = \vec{X}_\alpha - \vec{A}_1 \cdot (\vec{D}_\alpha) \quad (4)$$

$$\vec{X}_2 = \vec{X}_\beta - \vec{A}_2 \cdot (\vec{D}_\beta) \quad (5)$$

$$\vec{X}_3 = \vec{X}_\delta - \vec{A}_3 \cdot (\vec{D}_\delta) \quad (6)$$

$$X(t+1) = \frac{X_1 + X_2 + X_3}{3} \quad (7)$$

### Encircling prey

The prey's encircling by the grey wolves is modelled using Equations (8) and (9).

$$\vec{D} = |\vec{C} \cdot \vec{X}_{pi} - \bar{X} \quad (8)$$

$$\vec{X}_{1+1} = \vec{X}_{pi} - \vec{A} \cdot \quad (9)$$

Where $\vec{D}$ is the distance of the wolves from the prey, $\vec{X}_{pi}$ and $\vec{X}_i$ are the prey and grey wolf positions, respectively.

### *Attacking and Searching for prey*

Searching and attacking the prey correspond with the exploration and exploitation capabilities of the grey wolves. The variable vectors $\vec{A}$ and $\vec{C}$ Equations, (9) and (8) are presented in Equations (10) and (11), respectively. If the value of vector A is less than -1, the grey wolves will attack the prey. Otherwise, they would search for a better one.

$$\vec{A} = 2 \cdot a \cdot r_1 - a \quad (10)$$

$$\vec{C} = 2 \cdot r_2 \quad (11)$$

When the wolves are nearing the prey, this is equivalent to varying the operator $a$ from 2 to 0, while the vector $\vec{A}$ is reduced to a. The operators $r_1$ and $r_2$ lied between 0 and 1.

## METHODOLOGY

The methodology is presented in this section.

### Description of PI pitch control of Wind Turbine

The Wind Turbine aerodynamic power can be controlled using different types of control methodologies. The dominant one is the PI controller pitch angle control[10]. The pitch control system consists of the PI controller, pitch actuator, rate limiter and angle saturator. It is applied to limit the Wind Turbine's mechanical power operating above-rated wind speed to rated power [11] and [12]. The control objective is to adjust the pitch angle so that the aerodynamic power is limited to rated power using the control law expressed by Equation (12)[13], [14].

$$\beta_{bld}(t) = K_p^2(P_{nom} - P_{mech}) + K_i^2 \int_{t0}^{t} (P_{nom} - P_{mech})dt \quad (12)$$

Where $K_p$ and $K_I$ are proportional and integral gains of the PI controller in the aerodynamic power control loop of the pitch control. While $P_{mec}$ and $P_{nom}$ are Wind Turbine aerodynamic power and nominal power, respectively.

When the Wind Turbine's pitch angle increases, it leads to the limiting of its aerodynamic power to the rated value because of the non-linear inverse relationship between the pitch angle β and the power coefficient $C_p$ (λ, β) of the Wind Turbine. At full load operating region, the generator of the Wind Turbine runs at the rated speed to generate the rated electrical power $P_{nom}$.

### Structure of the Optimization of PI pitch control of Wind Turbine.

The block diagram of the proposed Optimization-PI pitch control structure of the Wind Turbine is shown in Figure 1.

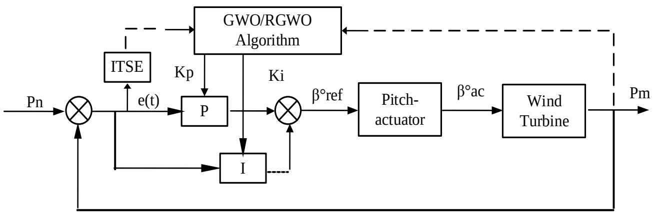


**Fig-1** Block diagram for GWO/RGWO-PI pitch control structure.

It consists of the PI controller, the pitch actuator (servo-motor), and the Wind Turbine all connected in series. In this study, the GWO and RGWO are proposed to fine-tune the gains of the PI controller in pitch control of the wind turbine. During PI controller tuning, the GWO/RGWO tuning block in Figure 1 is responsible for tuning the controller's gains. It continues to tune the gains of the PI controller while minimizing the ITSE of the power error $e$ of Equation (13) at the input of the PI controller. The power error is the difference between the aerodynamic power ($P_m$) of the Wind Turbine and its nominal power ($P_n$). The PI controller provides the pitch angle $\beta^{\circ}_{PI}$ in mechanical degree presented in Equation (14) to the pitch actuator. The $\beta^{\circ}_{PI}$ drives the pitch actuator to obtain $\beta^{\circ}_{reference}$ presented in Equation (15), the required adjustment of pitch angle to the rotor blades of the Wind Turbine [15].

$$e = P_n - Cp(\lambda,\beta)\frac{1}{2}\rho\pi R^2\left(\frac{\omega R}{\lambda}\right)^3 \qquad (13)$$

$$\beta^{\circ}{}_{PI}(t) = K_p * e(t) + K_i * \int_0^t e\,(t)dt \qquad (14)$$

$$\beta^{\circ}{}_{reference} = {}^{1}\!/_{(1+T_\beta s)} * \beta^{\circ}{}_{PI} \qquad (15)$$

## Formulation of the Transfer Function of the closed-loop Pitch Control of Wind Turbine

The first step in the proposed GWO/RGWO optimizations for the PI controller in the pitch control of the Fixed Speed Wind Turbine is to formulate the transfer function of the closed-loop system consisting of the controller, pitch control and the Wind Turbine shown in Figure 2. It is a negative closed-loop system.

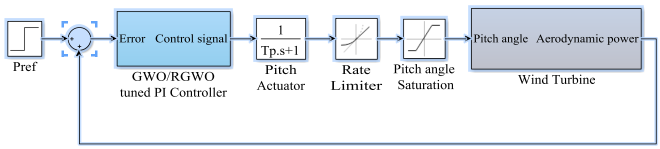


**Fig-2** Close-loop system for tuning the PI controller in pitch control of Wind Turbine

The transfer functions of the PI controller and pitch actuator are presented in Equations (16) and (17) respectively. The Fixed Speed Wind Turbine is presented as a second-order transfer function in Equation (18). Refer to for method of obtaining the Wind Turbine transfer function [16]. Since those transfer functions are for serially connected components shown in Figure 2, their equivalent transfer function is presented in Equation (19).

$$G_c(s) = K_p + K_i \qquad (16)$$

$$G_s(s) = \frac{1}{T_\beta * s +} \qquad (17)$$

$$G_{wt}(s) = \frac{K\omega_n^2}{s^2 + 2\zeta\omega_n s +} \qquad (18)$$

$$G_{wt}(s) = \left(\frac{K_p s + K_i}{T_\beta * s^2 + (1+K_p)s + K_i}\right)\frac{K\omega_n^2}{s^2 + 2\zeta\omega_n s +} \qquad (19)$$

Where K is the open-loop forward gain of the Wind Turbine, is its damping ratio, $\omega_n$ is the natural frequency parameter and $K_p$ and $K_I$ are the Proportional and Integral gains of the PI controller.

## Standard Objective Functions for Controller Tuning

The RGWO and the GWO are meta-heuristic algorithms that can be applied as instruments for computing the gains of controllers in tuning problems. The standard objective functions used by researchers for tuning the gains of the PI controller are the Integral Absolute of Error (IAE), the Integral multiplied Time Square of Error (ITSE), the Integral Square of Error (ISE), and the Integral Time multiplied Absolute of Error (ITAE) [17], [18]. These are presented in Equations (20) - (23).

$$IAE = \int_0^T |e(t)|dt \qquad (20)$$

$$ITSE = \int_0^T te^2(t)dt \qquad (21)$$

$$ISE = \int_0^T e^2(t)dt \qquad (22)$$

$$ITAE = \int_0^T t|e(t)|dt \qquad (23)$$

Where e(t) is the power error at the input of the PI controller, T is the simulation time, t is the instantaneous time, and dt is the sampling time.

**Formulation of ITSE Objective Function for PI pitch Controller Tuning.**

The objective function is based on the power error e(t) at the input of the PI controller in the closed-loop pitch control of Figure 3.6. The power error is already presented in Equation (13). Then the time domain power error was transformed into the s-plane using the Laplace Transform and is presented in Equation (24). The power error in the s-plane of Equation (24) was utilized to develop the ITSE standard objective function used to tune the gains of the PI controller in the pitch control. The tuning is modelled using Equation (25) to minimize a single objective function Min: ITSE with bounded Equation constraints (26).

$$e(s) = 1 - \left(\frac{K_p s + K_i}{Tp*s^2 + (1+K_p)s + K_i}\right)\frac{K\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (24)$$

$$Min{:}\ ITSE = \int_0^T te(s)^2 dt \quad (25)$$

Subject to: $lb \le K_p \le ub, \&\ lb \le K_i \le ub$ (26)

Where T is the simulation time, t is the instantaneous time, and dt is the sampling time.

The bounded constraints for the PI controller's optimal tuning are the upper and lower bounds of the controller's Proportional and Integral gains.

**Modifying the GWO updating parameter.**

The performance of metaheuristic algorithms depends on tuning and control of their parameter [5] tuning and parameter control. The updating positions of wolves from the best positions of Alpha (λ), Beta (β) and Delta (δ) wolves is illustrated in Figure 3.

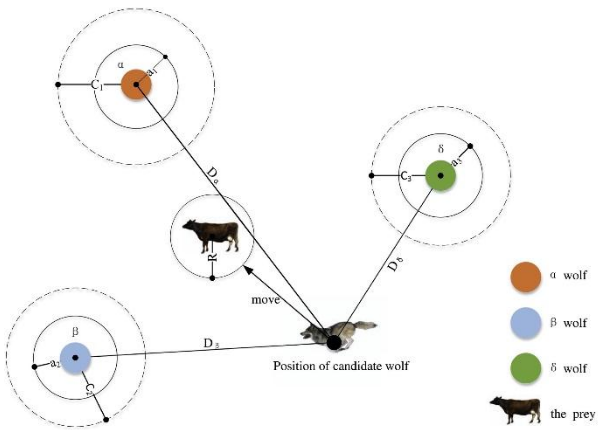


**Fig-3** Best position vectors $X_1$+$X_2$+$X_3$ of $\alpha$ $\beta$ and $\delta$ wolves [19].

The equal influences of Alpha (λ), Beta (β) and Delta (δ) wolves in Equation (7) which model the updating of the positions of wolves have violated the hierarchy class of the wolves and this has the possibility not to provide optimal tuning results. Therefore, the vector sum $X_1 + X_2 + X_3$ of $\alpha$, $\beta$ and $\delta$ wolves in the numerator of Equation (7) is modified by taking the square root of the sum $X_1^2 + X_2^2 + X_3^2$ as presented in Equation (27). The numerator of Equation (7) was replaced with Equation (27) to obtain the Resultant Grey Wolf Optimizer (RGWO).

**Optimal tuning of PI controller in pitch control**

$$X_r = \sqrt{X_1^2 + X_2^2 + X_3^2} \quad (27)$$

In this study, the GWO and RGWO were applied to tune the PI controller in pitch control of the three megawatts Squirrel Cage Induction Generator (3MW SCIG) Wind Turbine (see appendix). The number of variables to be optimized (dim) is 2, that is the PI gains. Five number (5) wolves were used to fine-tune the gains of the controller by minimizing the ITSE objective function in 30 maximum number of iterations. The lower and upper bound constraints were set to 0 and 25 respectively.

**Selected Parameters and Operators of the GWO and modified GWO.**

The selected parameters and operators of the GWO and the RGWO algorithms for the first search space [0, 25] [0, 25] of $K_p$ and $K_i$ gains, selected for tuning the PI controller in pitch control of the Wind Turbine were presented in Table 1. To run the GWO and RGWO codes for optimal tuning of the PI controller in the Wind Turbine pitch control, the controller's proportional and integral gains must be assigned as the position vectors, while the ITSE is assigned as the objective function. The GWO and RGWO execute steps to compute the PI controller's optimal gains while reducing the power error at the controller's input with its upper and lower gain bounds as constraints.

**Table-1:** The search space selected parameters and operators used for running the GWO and RGWO.

| Optimizer | No of Search agents | Max. no Iteration | Upper bound | | Lower bound | | No of Variable | Operators | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $K_p$ | $K_i$ | $K_p$ | $K_i$ | | | | |
| GWO | 5 | 30 | 5 | 25 | 0 | 0 | 2 | a= [2 0] | $r_1$= [0 1] | $r_2$= [0 1] |
| RGWO | 5 | 30 | 5 | 25 | 0 | 0 | 2 | a= [2 0] | $r_1$= [0 1] | $r_2$= [0 1] |

## TUNING RESULTS AND DISCUSSION

From the best case in Table 2, the GWO converged into the global optimum of $1.865 \times 10^{-01}$ in the 1st iteration while the RGWO converged in the 2nd iteration as shown in Figure 4. The worst convergence result is presented in Table 2, where the GWO converged into the global optimum of $1.865 \times 10^{-01}$ in the 17th iteration while the RGWO converged in the 11th iteration. The worst-case convergence curves of the two tuning techniques are shown in Figure 5. The convergence results show that the GWO convergence speed is enhanced by modifying the GWO parameter for updating the positions of the wolves from the best positions vectors of α, β and δ and wolves. Considering Table 2, the RGWO computed the least mean values of $K_P$ gain equal to 4.446 while the GWO computed a higher average value of $K_P$ equal to 5.00.

The RGWO computed the least average values of $K_P$ gains equal to 11.884 while the GWO calculated the higher average value $K_I$ equal to 12.547.

**Table- 2:** Tuning results for RGWO and GWO algorithms

| Para meter | Iterations before convergence | | $ITSE = \int_0^T t.\left(e(t)\right)^2 dt$ in 30 trials | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | $K_p$ | | $K_i$ | | ITSE | |
| | GWO | RGWO | GWO | RGWO | GWO | RGWO | GWO | RGWO |
| Best case | **1** | 2 | 5.00 | 4.9801 | 12.5138 | 8.3752 | **$1.865e^{-01}$** | **$1.865e^{-01}$** |
| Worst case | **17** | 11 | 5.00 | 5.000 | 12.6338 | 9.7096 | **$1.865e^{-01}$** | **$1.865e^{-01}$** |
| Mean | 8.97 | 3.87 | 5.00 | 4.446 | 12.5465 | 11.8843 | **$1.865e^{-01}$** | **$1.865e^{-01}$** |
| Std | 3.62 | 3.34 | 0.00 | 0.1006 | 0.0421 | 0.2317 | $8.871e^{-07}$ | $9.8293e^{-7}$ |

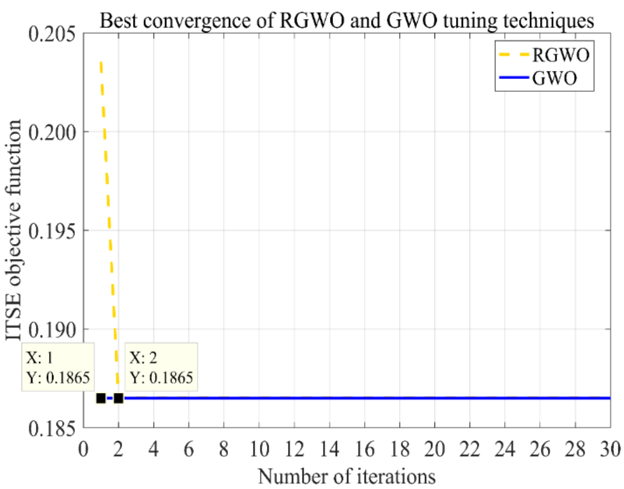


**Fig-4** Best convergence curves for minimized ITSE objective function for first search space [0, 25] [0, 25].

These tuning results obtained from RGWO and GWO indicate that replacing the numerator of best positions vectors of $\alpha$ $\beta$ and $\delta$ wolves of Equation (7) of the GWO with a vector presented in Equation (27) to form the RGWO has increased the convergence speed of the GWO and reduced the values of the PI tuned gains obtained from the GWO.

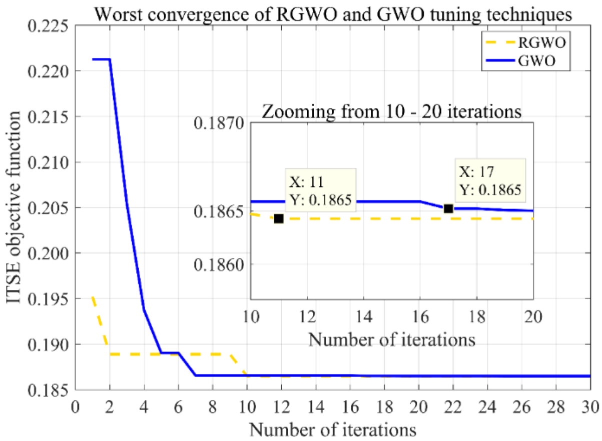


**Fig-5** Worst convergence curves for minimized ITSE objective function for first search space [0, 25] [0, 25]

## 3. CONCLUSIONS

The optimal tuning of the PI controller in pitch control of the wind turbine using GWO and RGWO is conducted, where the RGWO provided better-tuned gains and showed faster convergence than GWO. Both GWO and RGWO did not trap into a local optimum during the tuning of the PI controller. Therefore, it can be concluded that the RGWO tuning technique is better than GWO for the PI controller tuning in the pitch control of the Wind Turbine. The contribution of this study is the modification of updating parameter of the GWO parameter, which models the updating of wolves' positions from the best positions of α, β and δ wolves, and this enhanced the average convergence speed of the GWO. Furthermore, the modification of the GWO updating parameter provided better-tuned gains for the PI controller in the pitch control of the Wind Turbine. The faster settling time in pitch control of the Wind Turbine provided by the modified GWO can reduce the stress in the pitch control of the Wind Turbine compared to GWO.

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## BIOGRAPHY

Dr. Aliyu Hamza Sule is a Principal Lecturer Depart. of Elect. Eng'g at HUK Polytechnic Katsina. He obtained a Ph.D. in Electrical Engineering in 2021 from UTM, Malaysia. His research interests include Optimization of Power System using Metaheuristic Optimizers, Integration of RES in Power System, Power System Stability and Control.

APPENDIX

**Table-3:** SCIG Wind Turbine, Grid, Transformer and Line parameters [13]

| **SCIG Wind Turbine parameters.** | | | **Grid, Transformer and Line Parameters** | | |
|---|---|---|---|---|---|
| **Parameters** | **Value** | **Unit** | **Parameters** | **Value** | **Unit** |
| Rated power | 3 | MW | Rated voltage | 154 | kV |
| Rated speed | 12.5 | m/s | Rated frequency | 60 | Hz |
| Cut-in speed | 4 | m/s | TX-1 rating | 22.9/ 154/30 | kV/kV /MVA |
| Cut out speed | 20 | m/s | TX-2 rating | 690/ 22.9/4 | kV/kV /MVA |
| Rated V/Freq | 690/60 | V/Hz | Load | 500 | kW |
| Rs/Rr | 0.00488/ 0.00549 | Ω/Ω | Line-1 | 1x10 | km |
| L1s/L1r | 0.0924/ 0.09955 | Henry | Line-2 | 1x10 | km |
| Lm | 3.95279 | Henry | Line-3 | 1x1 | km |
| Qpf | 200 | kVar | | | |