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Optimal Design of Electric System for Off-shore Wind Power Plant (OWPP)

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Abstract- In the recent years, due to land scarcity, off-shore wind power installations have been increased tremendously over on-shore installations. Beside its numerous advantages, high initial investment is the major concern of off-shore wind power installation and it is the main striking hindrance for its development. In view of reducing the investment and operational cost of electrical network integrating Off-shore Wind Farm (OWF) to on-shore grid, the paper proposes a novel Optimal Frequency AC (OFAC) transmission system, designed based on the computation of optimum operational frequency. The proposed system is economically competitive compared to High Voltage AC (HVAC) and Low Frequency AC (LFAC) system for moderate distant power transmission. The optimum operational frequency is the result of tradeoff between investment and operational cost of electric system. The paper presents a comprehensive methodology for the computation of optimum operational frequency for OWPP based on the criterion of minimization of installation and operational cost using Genetic Algorithm (GA). The proposed methodology is applied to an OWF of 160MW capacity. And for the off-shore distances of 50km, 100km, 150km and 200km, the optimum frequencies are obtained as 85Hz, 55Hz, 35Hz and 25Hz respectively. As compared to HVAC and LFAC, the proposed system validates its viability and profitability for the moderate distant power transmission and the results indicate that for the transmission lengths of 100 to 225km, the proposed system yields a saving of about 2 to 10% in the Net Present Value (NPV) of the system. Hence it is concluded that the paper presents a newer dimension for the economical design of OWPP based on optimum frequency and it helps in the promotion of off-shore deployment to the investors.

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Keywords: optimum frequency, off-shore wind power plant, optimization, NPV.

1. Introduction

Harvesting energy from wind has become one of the major contributions to the energy sector across the globe. Due to policy instability as well as specific issues linked to land acquisition for wind power projects on land; deployment of wind project offshore has been increased in the recent times. High-stable offshore wind potential, large installation space, no visual effects, closeness of major load centres and technological advancement in the wind industry has supplemented its growth. Globally offshore installation has been progressed with an average growth rate of 30% per annum during 2010-2017, reaching to a total installed capacity of 18GW at the end of 2017 [1]. Opportunities for further scaling up are humongous. An ambitious target of 40GW by 2020 has been reported.

Huge initial investment is one of prominent slog in the path of offshore development. Highly evolved tower construction, offshore substation, seabed lying of submarine cable and high maintenance cost are some of reasons for heavy investment. And it is the major hindrance for offshore deployment. Presently, the Levelized Cost of Energy (LCOE) is more than $5-6 millions per MWh, and it warrants for the technological changes to reduce the investment, and make OWPP economically feasible [2].

In the OWPP, among the split-up, electrical infrastructure cost shares significant portion in the total project cost. It includes the cost of inter-farm distribution network which collects the power from the wind turbines and the cost of main transmission network which exports the power from the off-shore substation to on-shore grid. In broader perceptive, the paper exploits on opportunities to reduce the electrical infrastructure cost for OWPP.

In respect of this, a new transmission system i.e. Fractional Frequency Transmission System (FFTS) has been proposed in the literature as an economic alternative to HVAC and HVDC [3]. FFTS is also named as Low Frequency AC (LFAC) by some researchers. In the LFAC, power transmission is proposed at 1/3rd of the nominal frequency (50/60Hz), and at the grid-side, frequency converter is employed to transform fractional frequency (50/3Hz) to nominal frequency (50Hz). In the LFAC, due to low frequency operation charging current requirement of the cable is less and that increases its power transmission capacity, and unlike HVDC it requires only one converter at the grid-side are main attributes for its cost rduction [3].

The technical and economical feasibility of LFAC over conventional HVAC and HVDC has been investigated by many researchers [3]-[6]. It is stated that, LFAC has economic and performance advantages over conventional HVAC and HVDC. Many researchers have shown interest in LFAC for integrating OWF to on-shore grid [7]-[12].

The fundamental quest on the choice 50/3 Hz frequency for LFAC has initiated this paper. Literature states that, single-phase 50/3Hz system is already in-use for supplying electric power to traction in German and in LFAC cyclo-converter can be employed for frequency transformation which is less costly compared to other converters [8]. After a careful perusal of the literature, it is revealed that, the choice of 50/3Hz frequency for LFAC seems to be a compromise, and it is not based on any rigorous mathematical analysis. The choice of frequency for power transmission is very important, because it reflects on the project economy. The paper particularly deals with the choice of operational frequency for LFAC. Design of electric system for non-conventional frequency (other than 50/3Hz) is possible, simply by replacing Cyclo-converter with Back-to-Back DC Link Converter (BBDLC). Despite being costly, BBDLC meets the grid-code requirement of voltage and reactive power control capability. LFAC with optimum operational frequency leads to a novel transmission system, and in the paper it is referred to as Optimum Frequency AC (OFAC) transmission system.The existence of optimum operational frequency is the result of inherent tradeoff between two broad categories of costs of the system; one involving the cost of power cable network and second involving the cost of generators and transformers.Similar behavior of tradeoff can be observed for the losses between two categories. The paper presents a comprehensive methodology for the computation of the optimum operational frequency for OFAC,based on the minimization of installation and operational cost of electric system using Genetic Algorithm. The proposed methodology is applied to an OWF of 160MW capacity and the results show that the proposed OFAC system yields significant amount of saving in the overall expenditure.

The paper is organized as follows. The structure of OFAC and the concept of optimum operational frequency are presented in Section 2. Section 3 and 4 presents the development and the implementation of mathematical model. Section 5 discusses on the prototype OFAC for application of the developed methodology. The results are discussed in the Section 6, and finally, Section 7 concludes the paper.

2. Structure of OFAC and the concept of optimum operational frequency

Figure 1 shows the structure of the OWPP using the proposed OFAC system. In this system, the generators, transformers, inter-farm electric system and the transmission system, works at optimum frequency. At the grid-side, optimum frequency is transformed to 50Hz using frequency converter (BBDLC) and power is injected on-to the grid.

Similar structure based on LFAC has been proposed in the literature [13], called as Fractional Frequency Wind Power System (FFWPS). It eliminates individual power converter in the wind turbine and proposes speed control from single large power converter (cyclo-converter) [14]. Due to elimination of individual power converter the cost is reduced but there is a 3% loss in the energy yield [15]. Reference [16] has discussed synchronisation scheme for FFWPS and shown safe and reliable integration of offshore wind farm to onshore grid.

In this paper, the study on FFWPS is extended from the perspective of its operational frequency. At present the operational frequency of FFWPS is 50/3 Hz, but as discussed in the previous section, the choice of 50/3 Hz frequency seems to be compromise and it is not based on any formal mathematical analsysis. So, the paper deals with the computation of optimum operational frequency for FFWPS based on minimum cost criterion.

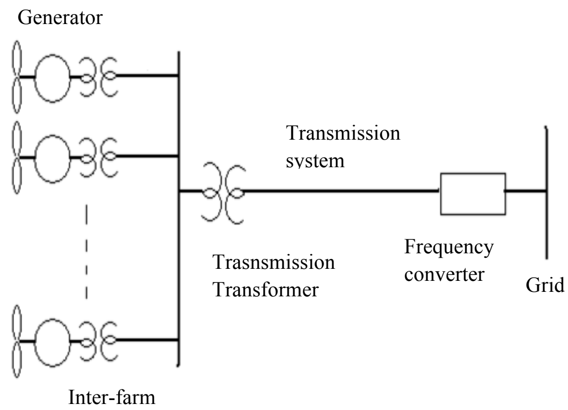

Fig. 1 Structure of OWPP using OFAC.

For the OWPP as shown in the Fig. 1, existence of optimum operational frequency is realized based on the investigation that, the cost of power system components such as generator, transformer, transmission line etc., varies with the frequency. Specifically, the cost of generator and transformer varies in inverse proportion to frequency, because, for the same power and voltage rating, the size of the magnetic system (no. of turns/ core area) decreases with frequency and hence the cost decreases. Whereas, the cost of power transmission system varies in direct proportion to frequency, because, as the frequency increases, the charging current requirement of the cable increases, and for the same active current, the size of the conductor increases with frequency and hence the cost increases. So it is realized that, there is tradeoff in the two broad categories of costs,

- Cost of power cable network
- Sum of the cost of generators and transformers

Figure 2 shows the typical variation of these two costs with respect to frequency.

So the electrical installation cost of OWPP, which is sum of these two costs will be parabolic in nature with respect to frequency. The point of inflection on the system cost curve corresponds to the optimum point. The X and Y co-ordinates of the optimum point corresponds to optimum operational frequency and the optimum installation cost respectively.

Similar behavior is observed for the loss as shown in the Fig. 3. It is investigated that, the total active power loss of OWPP which is sum of the loss of generator, transformer and transmission system is also parabolic w.r.t. frequency, and there also lies an optimum operational frequency at which the system power loss gets minimum. The operational cost that accounts for the expenses due to power loss obviously follows its very nature; it means that, as similar to power loss the operational cost will be also parabolic in nature w.r.t. frequency.

Thus the installation and operational cost of the OWPP system are found to be parabolic, getting minimized at two different operational frequencies.

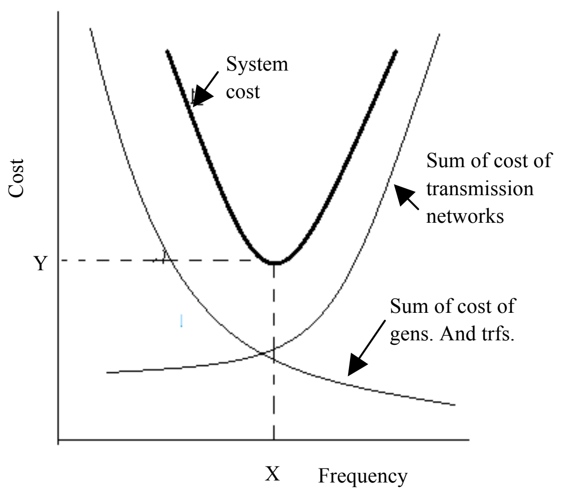

Fig. 2 Show the typical variation of costs for OWPP

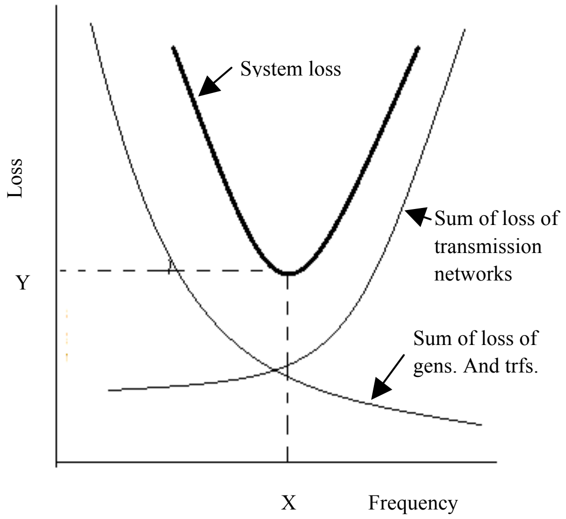

Fig. 3 Show the variation of losses for OWPP

This problem can be solved by multi-objective optimization algorithm which provides a set of optimum operational frequencies (Pareto optimal solutions) and by incorporating additional higher-level information, one single optimum operational frequency can be obtained. If OWPP is designed for this optimum operational frequency, it will have low installation cost as-well-as operational cost. This has initiated to define the objective of the paper as "**To compute the optimum operational frequency for OWPP based on the criterion of minimum installation and operational cost**". Development of mathematical model for the said objective is presented in the Section 3.

3. Development of mathematical model

With reference to the objective as laid-down in the previous section, it is clear that, the optimum operational frequency meeting the two conflicting objectives of minimization of investment cost as-well-as operational cost can be computed by two-objective optimization technique. In this paper these two-objective optimization problem is transformed into single-optimization by incorporating the above two objectives into a single objective in terms of Net Present Value of the system as defined in Equation (1).

$$\mathbf{NPV(f)=\{Plant_{cap}-Loss(f)\}*8760*PCF*UR-IC(f)} \quad (1)$$

where,

f – frequency(Hz), NPV – Net Present Value (M€), $Plant_{cap}$ – Plant capacity (MW), Loss – Active power loss (MW), PCF – Plant capacity factor, UR – Unit rate (€/MWh), IC – Installation cost (M€).

From the equation (1), it is evident that, since the installation cost and active power loss are parabolic in nature and they are in the negation form, NPV will be hyperbolic in nature. It implies that minimization of installation cost and active power loss is equivalent to maximization of NPV. So the objective function for optimization is defined as Equation (2).

$$\textbf{Maximize. } NPV(f)=\{Plant_{cap}-Loss(f)\}*8760*PCF*UR-IC(f) \quad (2)$$

Subject to,

$$1< f <100$$

Installation cost and power loss which are the function of frequency are defined as equation (3) and (4).

$$IC(f)=N*Cost_{gen}(f)+N*Cost_{inttrf}(f)+Cost_{inttrans}(f)+Cost_{transtrf}(f)+Cost_{trans}(f) \quad (3)$$

$$Loss(f)=N*Loss_{gen}(f)+N*Loss_{nttrf}(f)+Loss_{inttrans}(f)+Loss_{transtrf}(f)+Loss_{trans}(f) \quad (4)$$

where,

N – No. of wind turbines in the farm, $Cost_{gen}$– cost of generator (M€), $Cost_{inttrf}$ – cost of inter-farm transformer, $Cost_{inttrans}$ – cost of inter-farm transmission system, $Cost_{transtrf}$– cost of transmission transformer, $Cost_{trans}$ – cost of transmission system, $Loss_{gen}$– loss in generator (M€), $Loss_{inttrf}$ – loss in inter-farm transformer, $Loss_{inttrans}$ – loss in inter-farm transmission system, $Loss_{transtrf}$– loss in transmission transformer, $Loss_{trans}$ – loss in transmission system.

The cost and power loss of various power system components of OFAC such as; generator, inter-farm transformer, transmission transformer, inter-farm electric system, and transmission system are computed as follows.

3.1 Computation of generator cost and loss

Cost of the generator is estimated from its design parameters. For a given frequency, design parameters such as; main dimensions, number and size of stator slots, depth of stator core, dimension of rotor pole, depth of rotor core and number of stator and rotor turns etc. are computed using design equations (not presented). Copper and iron are major elements in the generator. So the cost of generator is estimated by considering only the cost of copper and iron. Table 1 in the Appendixprovides the details of design and performance parameters for 2MVA, 690V, 35rpm Synchronous generator for different frequencies as reference. It can be seen that, the cost of generator decreases with the frequency. Since the design parameters are subjective to design constants (variables), to obtain economy, design parameters and in-turn the generator-cost is optimized in terms of its design variables. Specific magnetic loading (B_{av}), specific electric loading (ac), width of ventilating duct (w_{ds}), width of stack length (w_{ss}), slot pitch (y_s), current density (δ) and Short Circuit Ratio (SCR) are selected as design variable with appropriate bonds. Mathematically the optimization is described as Equation (5),

$$\textbf{Minimize, } C_{gen}(B_{av}, ac, w_{ds}, w_{ss}, y_s, \delta, SCR) \quad (5)$$

$$C_{gen} = C_{ig} + C_{cg}$$

Subject to,

$$0.52 \le B_{av} \le 0.65$$

$$20000 \le ac \le 40000$$

$$8 \le w_{ds} \le 10$$

$$40 \le w_{ss} \le 80$$

$$10 \le y_s \le 50$$

$$3 \le \delta \le 5$$

$$1 \le SCR \le 1.5$$

where,

C_{ig} – Cost of iron of generator, C_{cg} – cost of copper of generator.

From the optimum design parameters, computed from the optimization as discussed above, performance parameters such as loss, efficiency and regulation are computed (Equations are not presented). Table1 in Appendix provides the performance parameters for 2MVA, 690V, 35rpm synchronous generator for different frequencies as reference. It can be seen that the loss in the generator decreases with the frequency.

3.2 Computation of transformer cost and loss

The cost of the transformer is estimated from its design parameters. For a given frequency, design parameters such as the core area, window dimensions, number of primary and secondary turns etc. are determined using design equations (not presented). Copper and iron are major elements in the transformer. So the cost of transformer is estimated by considering only the cost of copper and iron. Table 2 in the Appendix A provides the details of design and performance parameters for 2MVA, 0.69/33kV, 3-phase, core-type transformer for different frequencies as reference. It can be seen that the cost of transformer decreases with the frequency. Since the design parameters are subjective to design constants (variables), to obtain economy, design parameters and in-turn the transformer cost is optimized in terms of its design variables. A constant (K), as defined in Equation (6) is selected as design variable. Mathematically the optimization is described Equation (7),

$$K=4.44\times f\times (\varphi/AT)\times 10^3 \quad (6)$$

where,

f– frequency (Hz), *φ* – flux (wb), *AT* – ampere-turns (AT)

$$\textbf{Minimize, } C_{trf}(K) \quad (7)$$

$$C_{trf} = C_{itrf} + C_{ctrf}$$

where,

C_{itrf}– Cost of iron of transformer, C_{ctrf}– cost of copper of transformer

From the optimum design parameters computed from the optimization as discussed above, performance parameters such as loss, efficiency and regulation are computed (Equations are not presented). Table 2 in Appendix provides the performance parameters for 2MVA, 0.69/33kV, 3-phase, core-type transformer for different frequencies. It can be seen that the loss in the transformer decreases with the frequency. Cost and loss of inter-farm and transmission transformer are computed as per this methodology.

3.3 Computation of transmission system cost and loss

The cost of power transmission system is estimated as per by Equation (8). It includes only the cost of copper core. As per the standard practice, size of the core is assumed 50% more than the actual requirement.

$$\mathbf{C_{trans} = 3\times ((1.5\times I)/\delta) \times L \times S_c\times D_c} \quad (8)$$

where,

I - net current to be carried by the cable/phase (amps) ,δ – current density (amp/m^2), L – length of the cable (m), S_c- specific cost of copper (/kg), D_c –density of copper (kg/m^3).

The net current to be carried by the cable is calculated by adding the active current and the charging current as per Equations (9)-(11).

$$\mathbf{I = \sqrt{(Ia^2 + I_c^2)}} \quad (9)$$

$$\mathbf{I_a=P/ (\sqrt{3}\times V\times \cos\varphi)} \quad (10)$$

$$\mathbf{I_c= (V/\sqrt{3}) \times 2\times \Pi\times f\times C} \quad (11)$$

where,

I_a – active current /phase(amps), I_c – charging current/phase(amps), P – 3-phase power (W), V – line-to line voltage (V), $cos\varphi$ – power factor of load, f – frequency (Hz)C – Capacitance of the cable (F).

Power loss in the transmission system is computed by Equation (12). DC resistance is multiplied by 1.3 to take into account the skin effect.

$$\mathbf{Loss_{trans}= 3\times I^2\times 1.3\times R} \quad (12)$$

where,

R – DC resistance of the cable.

The cost and loss of inter-farm electric system and main power transmission system is calculated as per above methodology.

4. Implementation of mathematical model

The mathematical model developed in the previous section describes the optimization of Net Present Value model of the system to determine its optimum operational frequency. It also describes the optimization of generator cost and transformers cost. To implement this, a computational structure with two-stage optimization is developed as shown in the Fig. 4. In stage-I, the cost of generator, inter-farm transformer and the transmission transformer are optimized in terms of their design variables, whereas, the NPV cost model is optimized in terms of frequency in the stage-II. This unique feature of optimization ensures over-all optimization of the problem. Genetic Algorithm is used for all the optimizations.

Figure 5 depicts the process of computation of the optimum operational frequency. For simplification purpose, the working of Main-GA is only presented. Population size (pop-max) of 50 and maximum generation (gen-max) of 100 is assumed for implementing GA. The main core of the algorithm is the evaluation of fitness values (NPV Values)

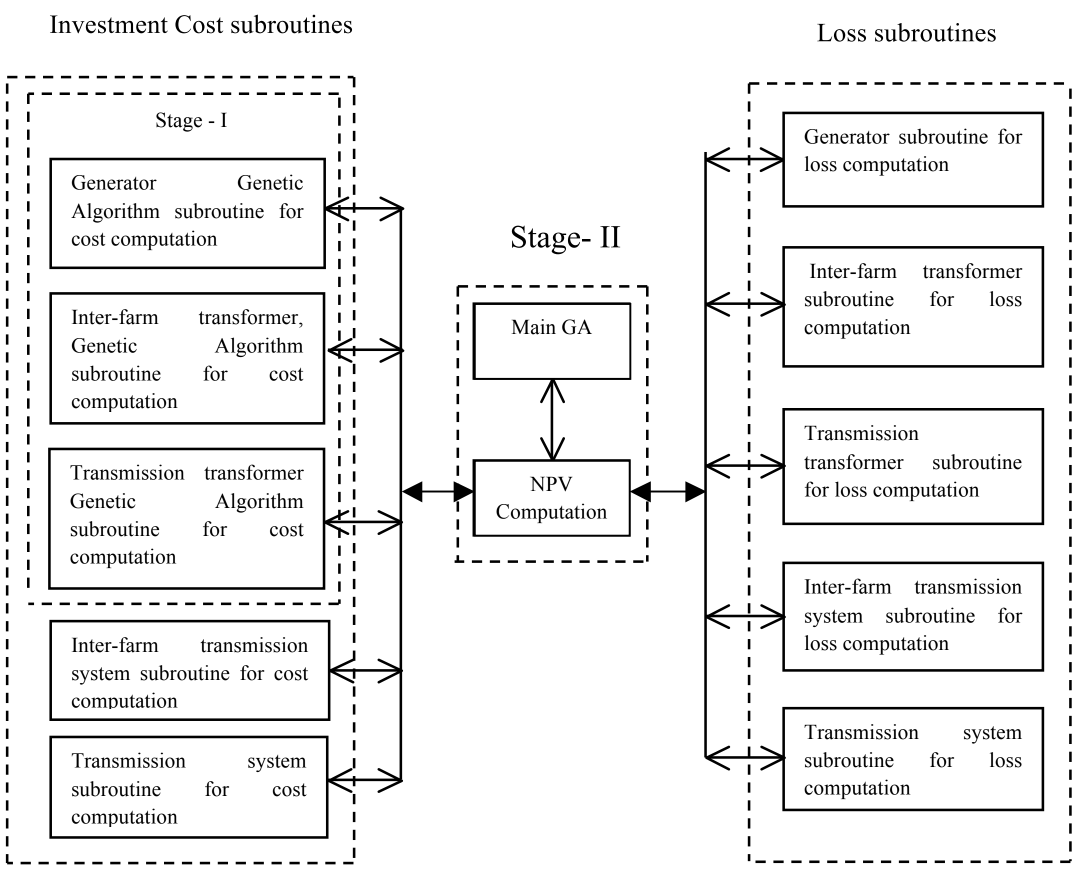

Fig. 4 Computational structure for implementation of mathematical model

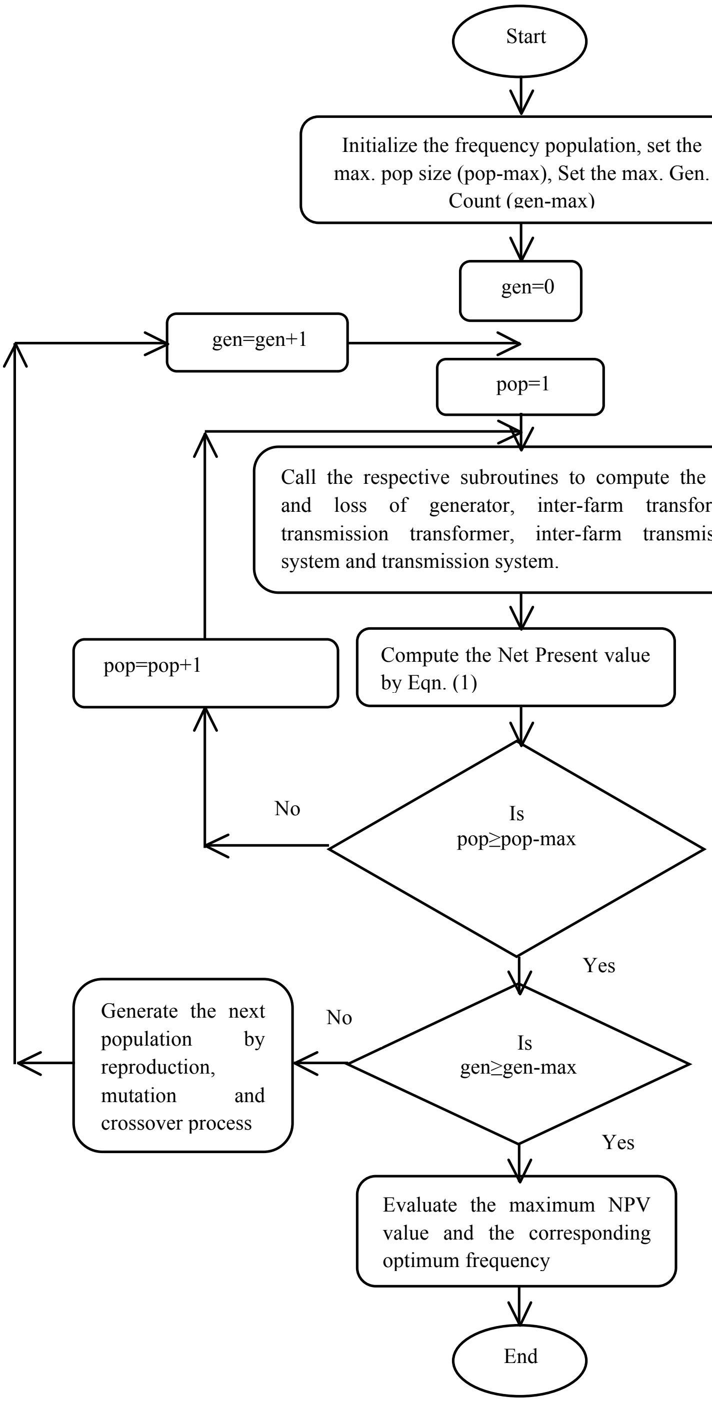

Fig. 5 Flow Chart show the process of implementation

for each generation. Initially, population for frequency is generated randomly. The population is represented by 8 bit number through encoding process. Then NPV values for each of the population are evaluated by extracting the values of cost and power loss of various power system components from the respective subroutines. The improvised population is generated through cross-over and mutation process. The populations between which cross-over is to be done and bit-position of crossover are selected randomly. Similarly bit-position for mutation process is also selected randomly. The population size is doubled in the cross-over process. Then through reproduction process the most favorite populations are selected for the next generation. The iterations of generations are continued with improvised generation in every-next iteration till maximum generation count is reached. Then finally, maximum fitness value of the last generation that corresponds to the optimum NPV value is evaluated. The population corresponding to the optimum NPV is the optimum operational frequency for OWPP.

5. Consideration of prototype OWPP for case study

To demonstrate the computation of optimum operational frequency, a prototype OWPP of 160MW capacity is considered for the case study. The wind farm is assumed to consist of 80 wind turbines each of 2MW capacity. The ratings of other power system components are given in the Table 3. These system parameters resembles to that of Horn-Rev off-shore wind power project.

6. Results and discussions

Based on the computational structure and the flow chart presented in the Section 4, code is written in MATLAB-7. The rating of power system components are initialized as per the prototype OWPP. The code is executed under different scenarios to obtain the following results.

6.1 Verifying the existence of optimum frequency

It was postulated in Section 2 that, the installation cost and power loss for OWPP are parabolic in nature with respect to frequency. To investigate this phenomenon, the costs of various power system components are estimated and there-from the system cost is estimated as per Equation (3) for different frequencies. Table 4 shows variation in the cost of power system components and the system cost for 100km transmission length. It can be seen that, the cost of generator, inter-farm transformer and transmission transformer decreases with the frequency, whereas the cost of inter-farm electric system and transmission system increases with the frequency. It can also be seen that, the system cost decreases initially up-to certain optimum frequency (indicated by shading) and then increases with the frequency.

Table 3 Rating of various components of prototype OWPP

Component	**Rating**
Generator	EESG: 2MVA, 690V, 35rpm
Inter-farm transformer	3-phase, core type: 2MVA, 0.69/33kV.
Inter-farm electric system	Submarine cable: 33kV,100km
Transmission Transformer	3-phase core type: 160MVA, 33/150kV
Transmission system	Submarine cable: 160MW,150kV, varying length

Table 4 Show the cost of components of prototype OWPP for different frequencies

(1)	(2)	(3)	(4)	(5)	(6)	(7)
10.00	0.41	0.15	18.80	1.24	58.61	123.41
20.00	0.23	0.08	19.14	0.68	60.50	105.36
30.00	0.17	0.06	19.70	0.52	63.54	101.70
40.00	0.13	0.04	20.45	0.42	67.56	102.72
50.00	0.12	0.04	21.38	0.35	72.41	106.26
60.00	0.10	0.03	22.46	0.31	77.95	111.31
70.00	0.10	0.03	23.68	0.28	84.05	117.75
80.00	0.09	0.02	25.01	0.26	90.61	124.62
90.00	0.08	0.02	26.43	0.24	97.54	132.39
100.00	0.08	0.02	27.94	0.22	104.79	140.60

(1) – Frequency (Hz), (2) – Generator cost (M€), (3) – Inter-farm transformer cost ((M€), (4) – Inter-farm transmission network cost (M€), (5) – Transmission transformer cost (M€), (6) – Transmission system cost (M€), (7) – Total investment (M€).

It is to be noted that, costs given in the table do not reflect to the real costs but should treated as an indicator of influence of frequency on the cost of components.

Figure 6 shows the system cost w.r.t. frequency. It can be seen that, the system cost gets optimized at certain optimal frequency. So it is proved that, the system installation cost of OWPP is parabolic in nature and there exist an optimum operational frequency at which the system cost gets minimal.

For OWPP with 100km transmission length, optimum operational frequency and optimum system installation cost are obtained as 30Hz and 101.69M€ respectively, indicated by red colored circle in the Fig. 6.

Similarly, power losses in various power system components are computed and there-from the total power loss is computed as per Equation (4) for different frequencies. Table 5 shows variation in the power loss for various power system components w.r.t. frequency for 100km transmission length. It can be seen that, the power loss of generator, inter-farm transformer and transmission transformer decreases with the frequency, whereas the loss of inter-farm electric system and transmission system increases with the frequency. It can also be seen that, the system loss decreases initially up-to certain optimum frequency (indicated by shading) and then increases with the frequency. Figure 7 shows variation in the power loss of system w.r.t. frequency. It can be seen that, the power loss gets optimized at certain optimal frequency. So it is proved that, the total power loss of OWPP is parabolic in nature and there exist an optimum operational frequency at which the system loss gets minimal.

For OWPP with 100km transmission length, optimum operational frequency and optimum system power loss are obtained as 55Hz and 29.39 MW respectively, indicated by red colored circle in the Fig.7.

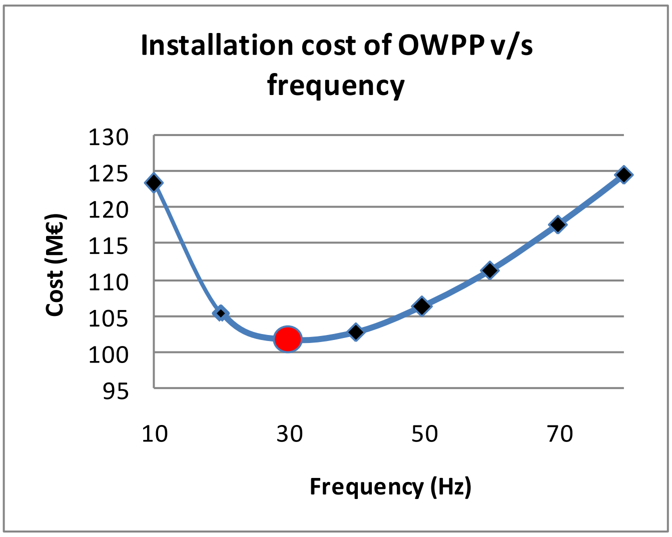

Fig. 6 The investment cost of electric system for prototype OWPP v/s frequency

Table 5 Show the loss of components of prototype OWPP for different frequencies

(1)	(2)	(3)	(4)	(5)	(6)	(7)
10.00	0.28	0.08	3.40	5.34	6.77	44.51
20.00	0.20	0.06	3.46	4.56	6.99	36.29
30.00	0.17	0.05	3.56	3.81	7.34	32.72
40.00	0.16	0.05	3.70	2.60	7.81	30.34
50.00	0.15	0.04	3.87	2.29	8.37	29.48
55.00	0.15	0.04	3.96	1.97	8.68	29.39
60.00	0.14	0.04	4.06	2.23	9.01	29.87
70.00	0.14	0.04	4.28	1.77	9.71	29.75
80.00	0.13	0.03	4.52	1.88	10.46	30.32
90.00	0.13	0.03	4.78	1.69	11.25	30.42
100.00	0.13	0.03	5.05	1.46	12.08	31.21

(1)–Frequency (Hz), (2) – Generator loss (MW), (3) – Inter-farm transformer loss ((MW), (4) – Inter-farm transmission network loss (MW), (5) – Transmission transformer loss (MW), (6) – Transmission system loss (MW), (7) – Total system loss (MW).

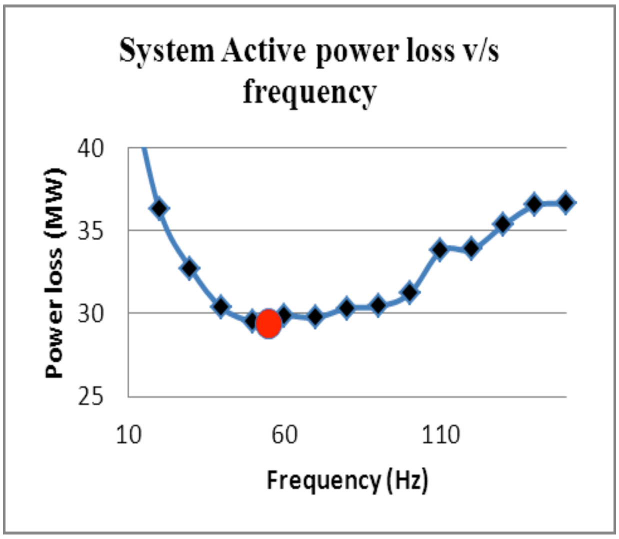

Fig. 7 Show the system power loss of prototype OWPP for different frequencies

Thus, it is verified that installation cost and system power loss for the given OWPP gets optimized at two different operational frequencies. To avoid the conflict between these two frequencies for two-objective optimization, single optimization involving NPV model has been developed. For the given OWPP of 160MW capacity and with the assumption of Plant Capacity factor (PCF) =0.3 and Unit Rate (UR) =43.1€/MW, NPVs are computed as per Equation (1) for different frequencies as shown in Fig. 8.

It can be seen that NPV of the system is hyperbolic in nature w.r.t. frequency and it get maximized at certain optimum frequency.

For OWPP with 100km transmission length, NPV of the system and the corresponding optimum frequency are obtained as 14.79T€ and 55Hz respectively, indicated by red colored circle in Fig. 8.

Thus, it is verified that, for the given OWPP, there exist an optimum operational frequency and if the system is

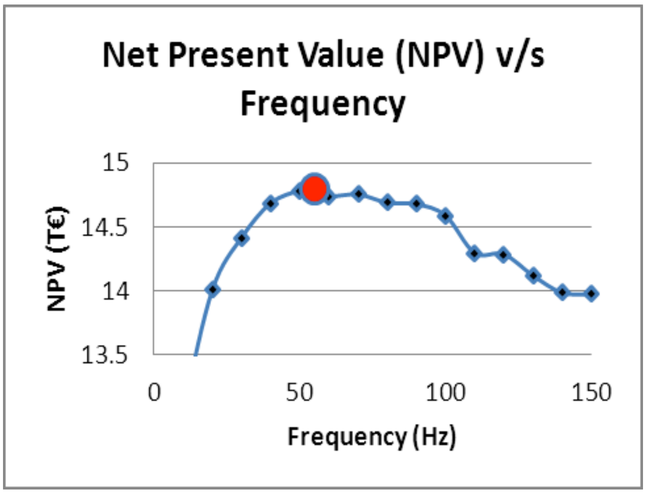

Fig. 8 Net Present Value v/s frequency

designed and operated at this optimum frequency significant saving in the overall expenditure can be extracted.

Since an optimum operational frequency depends upon the transmission length, with the aid of **Main-Genetic Algorithm,** optimum operational frequencies for different transmission lengths are computed as shown in the Fig. 9.

It can be seen that optimum operational frequency decreases with the transmission length. For the given prototype OWPP, and off-shore distances of 110km and 250km, optimum operational frequencies are obtained as 50Hz (red circle) and 50/3Hz (blue circle) respectively. It complies with the fact that, HVAC (50Hz) is economical for short distance transmission whereas HVDC (0Hz) is economical for long distance.

6.2 Economical benefits from the proposed Optimum Frequency AC (OFAC)

From the foregoing discussions, it is clear that, for the given OWPP, there exists an optimum operational frequency at which Net Present Value of system gets maximal. It implies that, if the OWPP is designed based on Optimum Frequency AC (OFAC) system, significant saving in the investment cost

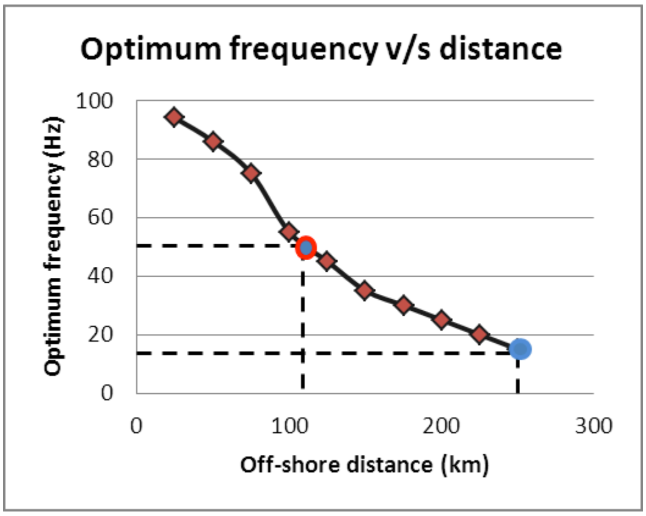

Fig. 9 Optimum operational frequencies for different off-shore distances

and operational cost can be achieved. Fig. 10 shows the NPV computations for the given prototype OWPP based on OFAC, LFAC and HVAC for different transmission lengths.

It can be seen that, OFAC system for OWPP provides higher saving as compared to HVAC and LFAC. Even-though OFAC proves its profitability for the entire range of transmission length, but its marginal advantage can be extracted for the range of 100km-225km, for which the operational frequency lies in the range of 50-50/3Hz. It means that, up-to 100km HVAC can be adopted and beyond 225km LFAC can be adopted for the OWPP. To quantify the economics of OFAC, savings accrued from this system compared to HVAC and LFAC are computed as shown in the Fig. 11. The savings are computed as per the Equation (15).

$$\textbf{Saving}=(\textbf{NPV}_{OFAC}-\textbf{NPV}_{HVAC/LFAC})/\textbf{NPV}_{HVAC/LFAC}\times\textbf{100} \quad (15)$$

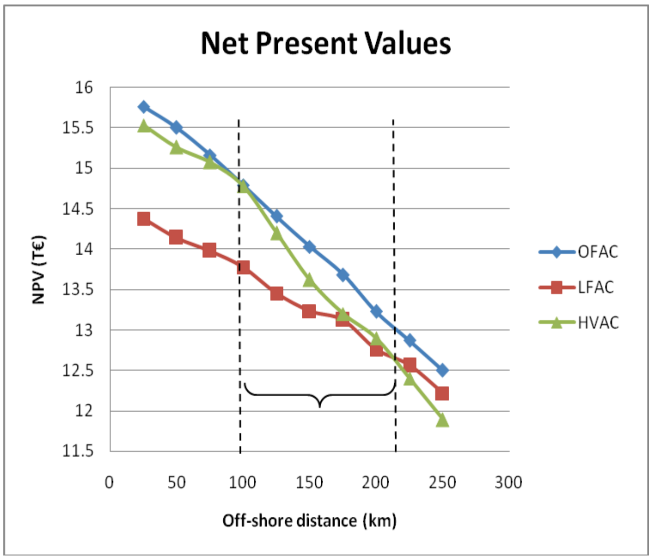

Fig. 10 NPVs for given prototype OWPP based on OFAC, LFAC and HVAC

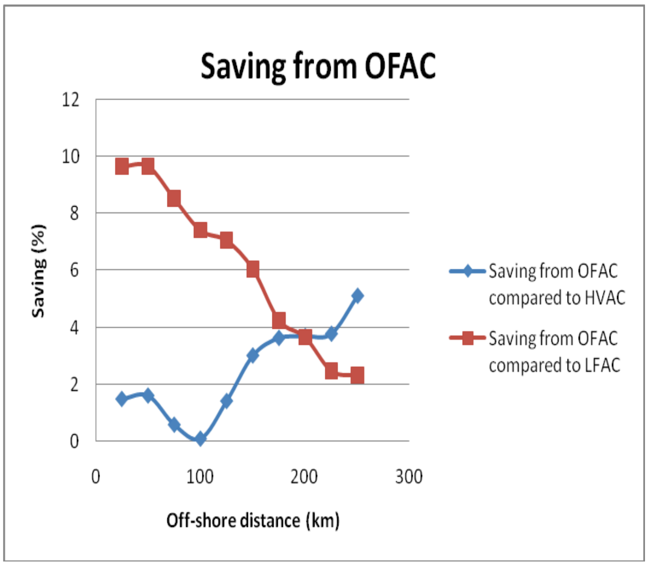

Fig. 11 Savings from OFAC compared to HVAC and LFAC

It can be seen that, OFAC provides saving up-to 10% as compared to LFAC and up-to 5% as compared to HVAC. Thus, it is proved that, if OWPP is designed based on OFAC, significant saving in the investment and operational cost can be achieved.

7. Conclusions

The paper has addressed the issue of high investment and operational cost of electric system of OWPP, through the proposal of a novel Optimum Frequency AC (OFAC) transmission system for integrating OWF to on-shore grid. OFAC is designed for the optimum operational frequency which is computed as a result of tradeoff between investment and operational cost. The paper has presented the insight characteristics of influence of frequency on the cost and power loss of power system components and recognized the tradeoff among them as the fundamental fact for the existence of optimum frequency and its computation. A comprehensive methodology for the computation of optimum frequency for the electric system has been developed. The developed methodology has been applied to a prototype OWPP and it is shown that, the proposed system yields a significant saving in the investment and operational cost. So it is concluded that, the proposed OFAC system for OWPP gives a new dimension in planning and cost effective design of electric system and can be emerged as a promising economical alternative to HVAC and LFAC for moderate distant power transmission. The work carried out in this paper will definitely encourage the investor for deployment of OWF which indirectly contribute in the reduction of air pollution and global warming which are the major concerns of world today in the endeavor. In the present work the cost of component is estimated based upon the cost of copper and iron requirement. So the study can be extended in the future by considering actual cost of the components, further operating voltage of the transmission systems can be added in the optimization for enhancing the results.

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Appendix

Table 1 Design and performance parameters of 3-phase, 2MVA, 0.69kV, Electrically Excited Synchronous Generator for different frequencies

Design and performance parameters	5Hz	10Hz	50/3Hz	20Hz	25Hz	30Hz	35Hz	40Hz	45Hz	50Hz
Optimal Cost (M €)	0.7355	0.4152	0.2661	0.2291	0.1935	0.1689	0.1490	0.1360	0.1258	0.1166
Stator Bore Diameter (m)	3.9244	4.5426	5.2074	5.5080	5.8600	6.2130	6.4700	6.7840	6.9900	7.2640
Stator Length (m)	0.8219	0.6205	0.4674	0.4220	0.3760	0.3370	0.3080	0.2842	0.2649	0.2481
Poles	18	34	58	70	86	104	120	138	154	172
Turns/pole	51	56	66	69	72	77	80	85	86	88
Flux/pole (wb)	0.3655	0.1668	0.0849	0.0677	0.0519	0.0404	0.0334	0.0275	0.0242	0.0213
Volume of stator iron (m^3)	1.8363	0.8836	0.4656	0.3753	0.2871	0.2267	0.1791	0.1484	0.1259	0.1060
Volume of stator copper (m^3)	0.2026	0.1624	0.1482	0.1426	0.1363	0.1345	0.1320	0.1329	0.1281	0.1258
Volume of rotor iron (m^3)	3.3626	1.8963	1.1727	0.9993	0.8236	0.6951	0.6032	0.5330	0.4825	0.4446
Volume of rotor copper (m^3)	0.2841	0.2210	0.1982	0.1805	0.1720	0.1681	0.1571	0.1527	0.1520	0.1430
Loss (MW)	0.4197	0.2839	0.2289	0.2118	0.1833	0.1739	0.1632	0.1585	0.1539	0.1485
Efficiency (%)	79.400	85.100	87.910	88.840	89.670	90.170	90.690	90.940	91.230	91.540
Stator temp rise (^{0}c)	196.05	141.89	107.00	98.210	88.720	77.610	75.970	68.350	66.194	64.250
Rotor temp rise (^{0}c)	236.32	214.99	190.32	188.73	174.63	164.77	160.75	159.32	144.42	144.54

Table 2 Design and performance parameters of 3-phase, 2MVA, 0.69/33kV, core-type transformer for different frequencies

Design and performance parameters	**5Hz**	**10Hz**	**50/3Hz**	**20Hz**	**25Hz**	**30Hz**	**35Hz**	**40Hz**	**45Hz**	**50Hz**
Optimal Cost (M €)	0.2350	0.1447	0.0999	0.0838	0.0678	0.0571	0.0496	0.0434	0.0391	0.0354
Constant (k)	0.1150	0.1524	0.3353	0.3556	0.3830	0.4064	0.4350	0.4427	0.4669	0.4801
Core area (m^2)	0.1544	0.1023	0.1351	0.1194	0.1029	0.0910	0.0835	0.0743	0.0697	0.0645
Primary turns	77	60	28	25	25	24	24	21	21	21
Secondary turns	3705	2795	1275	1200	1100	1050	975	950	900	875
Width of transformer (m)	1.9492	1.5867	1.8230	1.7138	1.5907	1.4960	1.4328	1.3521	1.3092	1.2594
Height of transformer (m)	1.3875	1.1294	1.2977	1.2199	1.1323	1.0648	1.0199	0.9624	0.9319	0.8965
Volume of core (m^3)	6970	3760	5700	4730	3790	3150	2770	2330	2110	1880
Volume of copper (m^3)	6180	4230	439	400	359	338	317	309	269	266
Loss (MW)	0.1258	0.0831	0.0717	0.0614	0.0549	0.0513	0.0431	0.0469	0.0407	0.0395
Efficiency (%)	92.7658	95.066	95.858	96.311	96.661	96.895	97.380	97.153	97.519	97.500
Regulation (%)	4.5138	3.4294	19.519	21.298	26.561	32.104	21.080	49.623	38.329	47.159
No-load current as % of full load current (%)	7.2447	5.9768	11.522	12.000	11.134	10.882	12.368	9.8491	10.792	10.386