Design of Electrical System for Offshore Wind Power Plant (OWPP)

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Abstract. *The paper proposes a novel Optimum Frequency AC (OFAC) transmission system for reducing investment and operational cost of Electric System (ES) - integrating Offshore Wind Farm (OWF) to the onshore grid. Optimum operational frequency for ES is an inherent characteristic of the trade-off between its investment and operational cost. The paper presents a comprehensive methodology for the design of ES based on Life Cost Analysis using a Generic Algorithm. For the given offshore wind farm, alternative designs for ES are generated for different operational frequencies. Power system components of standard ratings are used for the designs. All the designs are evaluated in terms of Net Present Values (NPV) and the design with maximum NPV is selected as the optimum solution. For 200 MW OWF, optimum operational frequencies are obtained as 50, 35, 25, and 50/3 Hz for offshore distances of 50, 100, 150, and 200 km, respectively. The results show that for 200 MW the feasible range for OFAC is 100–150 km and provides the saving of 5–10 % as compared to High Voltage AC (HVAC) and Low-Frequency AC (LFAC). The results further indicate that for large-scale wind farms the saving increases substantially and the feasible range is reduced. It concludes that OFAC is an economical alternative to HVAC and LFAC for integrating large-scale OWF to the onshore grid and provides a new dimension for promoting Offshore Wind Power Plant (OWPP).*

Keywords

Cost model, FFTS, Offshore Wind Farm, optimum frequency.

1. Introduction

Due to policy instability, as well as specific issues linked to land acquisition for wind power projects on the land, deployment of wind projects offshore have been increased in the recent past. Globally, on an average 6.1 GW of new installations have been commissioned annually during 2018–2020, accounting for the total installed capacity of 35 GW at the end of 2020 [1]. Opportunities for further scaling up are humongous. Cumulative Annual Growth Rate (CAGR) of 31.5 % is expected in the next five years and an ambitious target of 70 GW by 2025 has been reported.

The major concern of OWPP is its high cost. At present, the Levelized Cost of Energy (LCOE) is more than 85 $\$\cdot\text{MWh}^{-1}$. It warrants technological changes to reduce the cost and make OWPP economically viable [2]. In OWPP, the cost of an Electric System (ES) bears the substantial expenditure of the total project cost. It is typically around 15 to 30 % [3]. The ES consists of mainly three differentiated parts: Internal Distribution Network (IDN) that collects power from the wind turbines, offshore substations, and the Power Transmission Network (PTN) that exports power from offshore substations to the onshore grid. At the outset, the paper emphasis opportunities reducing the cost of ES and proliferating offshore deployment.

The optimal placement of wind turbines and their interconnection has been identified as one of the key areas for reducing the cost of ES. The authors in [4], [5] and [6] have done optimization of turbine placement using Genetic and Viral based algorithms and shown improvement in the energy yield-enhancing economics of ES. The authors in [7], [8], [9], [10] and [11] have dealt with the optimal interconnection of turbines using minimum spanning tree algorithm and Genetic based search algorithms and shown reduction in the cost of ES. The selection of adequate PTN has been identified as another prominent area for reducing the cost of ES.

The HVAC, Line Commutated Converter (LCC) based HVDC, and Voltage Source Converter (VSC) based HVDC is the various PTN options for integrating OWF to the onshore grid. Techno-economic evaluation of HVAC and HVDC has been performed by many researchers [12], [13], [14], [15], [16], [17] and [18]. It aims at the computation of Break-Even-Distance (BED). Transmission loss, reliability, and cost are generally the measures employed for evaluation. The results indicate that HVAC is feasible up to 50 km. Besides HVAC and HVDC, Reference [19] has proposed a new transmission system i.e., Fractional Frequency Transmission System (FFTS) is an economical alternative to HVAC for integrating OWF to the onshore grid. Many researchers have shown interest in this new transmission technology. Techno-economic evaluation of LFAC over HVDC and conventional HVAC has been investigated in [20], [21], [22], and [23]. It is stated that LFAC has economic and performance advantages over HVAC and HVDC.

Even-though the previous research work solves the problem to some extent, but it is subjective and has limitations in respect of its applicability. For this reason, the authors in [24] have proposed a novel transmission system, the Optimum Frequency AC (OFAC). The basic notion of OFAC is to transmit the power at the optimum frequency. In the proposed system, along with the contemporary design procedures, special emphasis has been given to operational frequency. Electro-magnetic behavior of power system components such as generator, transformer, cable, compensation unit, etc. depends upon the frequency and hence their cost, as well as ohmic loss, is greatly influenced by frequency. The operational frequency for power transmission and its relation to the cost of transmission system has been studied and it has been shown that investment and operational cost bear a parabolic relation with the operational frequency [24]. Further, it was shown that Optimum operational frequency is an inherent characteristic of the trade-off between its investment and operational cost; it is major contribution of authors to the literature. In [24], [25] and [26], the authors have presented a comprehensive methodology for the computation of optimum operating frequency based on minimization of investment and operational cost. It is shown that OFAC is a promising competitor to HVAC and LFAC.

In this paper, the research has been extended to update the design in respect of the following practical constraints:

- Previous design was based on the Fractional Frequency Wind Power System (FFWPS) wherein the power converter has been eliminated, and therefore the Wind Turbine Generator (WTG) was required to be redesigned for low-frequency operation [22]. For the low-frequency operation, the size of WTG increases and that causes a burden on the tower and foundation. So, in the updated design, the TYPE-IV WTG has been employed. It is a Variable Speed Fixed Frequency (VSFF) wind turbine generator. With the aid of an in-built power converter (AC-DC-AC), wind turbines can generate any desired frequency within the range of 1–50 Hz, and it does not warrant any significant changes except inter-farm transformer which can be redesigned for low-frequency operation.

- In the previous design, the cost and power loss of various power system components were computed from their design parameters. Whereas in the updated design, they are being calculated from the real market values available in the literature.

- In the present design, the operating voltages for IDN and PTN are optimized through an adequate selection of cables satisfying operating constraints.

- Transformers and cables of standard ratings are selected.

- In the previous design, the Net Present Value of the system was computed based on Plant Capacity Factor (PCF). But practically, PCF will not be known accurately. So, in the present design, the NPV equation has been modified suitably.

So, the objective of the paper has been defined as to optimize ES using OFAC for reducing its investment and operational cost considering all the practical constraints. With this introduction, the paper is organized as follows. Section 2. outlines the structure of OWPP for optimum frequency operation. The methodology for generating alternative designs for ES and their economical evaluation is discussed in Sec. 3. The influence of frequency on the power system components and the development of their cost and loss models is described in Sec. 4. Section 5. presents the results for different case studies. Finally, Sec. 6. concludes the paper.

2. Structure of ES for Optimum Frequency Operation

The structure of ES for optimum frequency operation is outlined as shown in Fig. 1. Wind turbines are assumed to be based on Variable Speed Fixed Frequency (VSFF). With the aid of an in-built power converter (AC-DC-AC), wind turbines can generate any desired optimum frequency within the range of 1–50 Hz. At the grid side, optimum frequency is converted to the grid frequency using a frequency converter, and power is injected onto the grid. Power converters at either end allow power transmission at the desired optimum frequency. This structure uses contemporary wind turbines (TYPE-IV) and does not require any significant changes except that transformers and compensators need to be redesigned for low-frequency operation. But this is not of major paramount. Furthermore, the existing submarine cables can be employed for power transmission. Back-to-Back DC-link power converter is state-of-the-art, despite being costly it meets the grid code requirements of voltage and reactive power control. So, this structure is implementable for optimum frequency operation and does not warrant any significant changes.

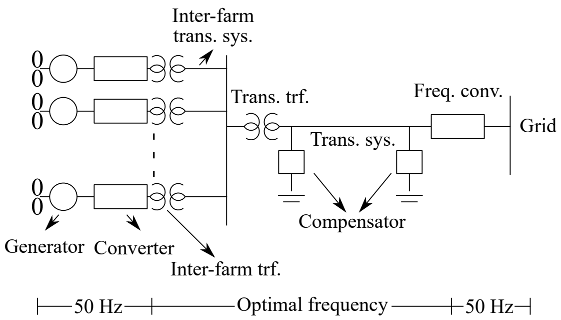

Fig. 1: Structure of electrical system for offshore wind power plant.

3. Methodology for the ES Design

The flow diagram for the design of ES based on OFAC has been developed as shown in Fig. 2. For the given wind farm inputs, various possible design alternatives for Inter-farm Distribution Network (IDN) and Power Transmission Network (PTN) are generated, and when they are combined (permutation and combination) to obtain a set of designs for the electric system. Such sets are obtained for the range of frequency 1 to 50 Hz. All designs are then evaluated in terms of Net Present Values to get the optimum frequency-based design for ES.

3.1. Generation of Alternative ES Design

Submarine cables are available in a wide range of voltage and current ratings as a single core or three cores. So, for the given power rating alternative designs for IDN and PTN can be generated. Following are the assumptions made for the generation of designs:

- The rating of the transformer is assumed 10 % more than transmission capacity.
- Single run cable is assumed with no redundancy.
- For IDN, cable connecting string to the offshore grid is selected equivalent to string capacity. For PTN, cable connecting offshore grid to onshore, is selected equivalent to wind farm capacity.
- String cable for IDN and main power cable for PTN are selected such that voltage and current at any point along the cable length should be 10 % less than the actual voltage and current rating of the cable. Voltage and current profile along the cable are calculated performing Load Flow (LF).
- The rating of the compensator is selected equal to reactive power loss of the cable.
- The rating of the frequency converter at the grid side is assumed to be equal to the wind farm capacity.

Thus, for the given wind farm inputs alternative designs for IDN and PTN are generated. Then, these two designs are combined to obtain different possible design alternatives for ES.

3.2. Economical Evaluation

Net Present Value (NPV) has been used as a measure for Life Cost Analysis of the design. The NPV for each design is determined as initial investment plus the discounted cost of annual losses in the system produced during the lifetime of the installation. Calculation of investment and energy loss has been detailed in Sec. 4. The NPV of the design alternative x, is calculated using Eq. (1), referenced from [27]:

$$NPV(x) = -Inv(x) - Eloss \cdot UR \cdot \left\{ \frac{\left(\frac{1+e}{1+i}\right)\left(1-\left(\frac{1+e}{1+r}\right)^n\right)}{1-\left(\frac{1+e}{1+r}\right)} \right\}, \qquad (1)$$

where, n is life span in (years), Inv is an investment in (€), Eloss is the annual electric energy loss

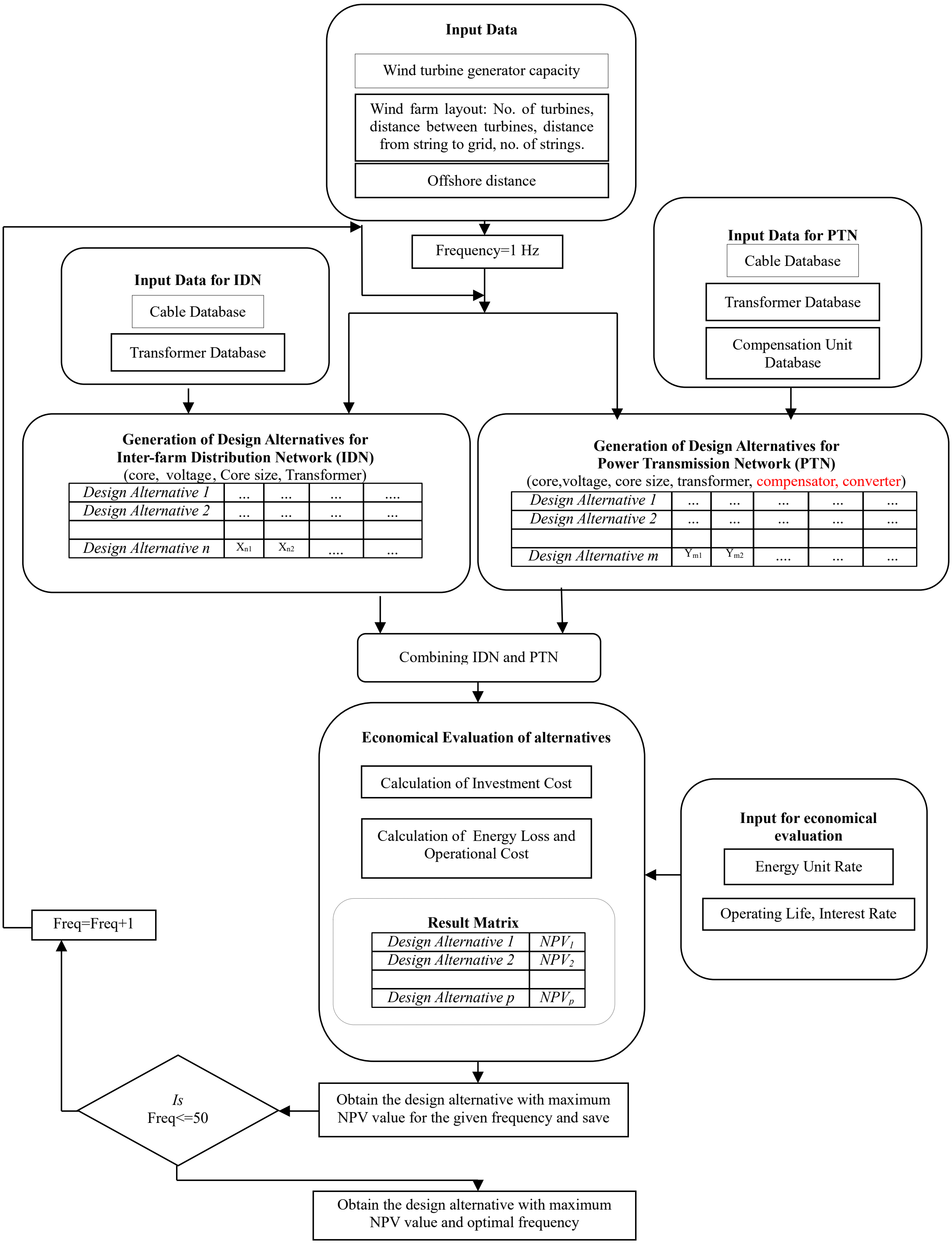

Fig. 2: Flow diagram for the design of ES.

in the transmission system in (kWh), UR is the unit rate in (€·kWh^{-1}), r is the rate of interest in (%) and e is the escalation rate in (%).

It is important to note that in Eq. (1) income from the sale of energy is not included, since this work is focused on the electric system and not on the complete OWF that would require further economic analysis. Therefore, all the terms have a negative sign. The net present value corresponds to the total discounted cost of the installation.

3.3. Decision Criterion

Optimum frequency-based design for ES is selected based on maximum net present value. It is accomplished in two processes (see Fig. 2). In the first process for the given wind farm inputs, various possible design alternatives for Inter-farm Distribution Network (IDN) and Power Transmission Network (PTN) are generated for one of the operational frequency (e.g. 1 Hz) and then they are combined to obtain the set of possible designs for the ES. Then, the NPV's are calculated for each of the designs and the design with maximum NPV is selected as the optimum design for that frequency. In the second process, such optimal designs are obtained for all the frequencies (1 to 50 Hz). Finally, from this set of designs, the design with maximum NPV is selected as the optimum design for ES, and the corresponding frequency gives optimum operating frequency for given OWF.

4. Calculation of Investment and Operational Cost

Transformer, cable, compensator, etc. are the major components of the electric system. In the proposed OFAC system, these components operate at non-conventional frequency. The cost and power loss of these non-conventional components are not available in the literature, and they must be derived from conventional 50 Hz values. Mapping functions for transforming cost and power loss of 50 Hz components to any other fractional frequency component have been developed as below.

4.1. Transformer Cost

The cost of a 50 Hz transformer for different VA ratings is given in [28]. It is re-produced here in Eq. (2):

$$Cost_T = A + BQ_{50}^{\beta}, \tag{2}$$

where, $Cost_T$ is the cost of 50 Hz transformer in (SEK), Q_{50} is the rating of 50 Hz transformer in (VA), $A = -1.208 \cdot 10^6$, $B = 2143$ and $\beta = 0.4473$. As discussed above, the cost given in Eq. (2) needs to be mapped to a non-conventional frequency scenario. For this, it is necessary to understand the effect of frequency on the cost which can be derived from EMF Eq. (3):

$$E = 4.44 f \Phi, \tag{3}$$

where, E is voltage/turn in (volts), f is the frequency in (Hz), Φ is flux in (Wb).

Referring Eq. (3), for constant flux (Φ) voltage per turn (E) varies proportionately with the frequency. It implies that voltage, as well as VA rating of the transformer, varies proportionately with the frequency. For example, for constant flux and current rating, voltage, and VA rating of 50 Hz, the transformer gets halved for 25 Hz. Thus, for constant flux and current, the VA rating of the transformer is proportional to frequency. So, we can have the following relation:

$$\frac{Q_{50}}{Q} = \frac{50}{f}, \tag{4}$$

where, Q is the VA rating of f Hz transformer in (VA) and f is the frequency in (Hz).

Equation (3) and Eq. (4) can be combined to obtain a frequency-based cost model of the transformer as given in Eq. (5):

$$Cost_T(f) = A + B\left(\frac{50Q}{f}\right)^{\beta}. \tag{5}$$

4.2. Power Loss in Transformer

Maximum permissible power loss for 50 Hz transformer for different ratings has been obtained from [29] as given in Tab. 1:

Tab. 1: Core and copper loss of 50 Hz transformer.

MVA rating	12.5	20	31.5	40	50	63	85	100
Core loss (kW)	9	12	18	21	24	32	40	46
Copper loss (kW)	62	96	135	175	200	240	278	357

Core and copper loss tabulated in Tab. 1 are fitted with respect to rating of 50 Hz transformer as Eq. (6) and Eq. (7) respectively:

$$Core\,loss = 0.0004253\,Q_{50} + 0.003877, \tag{6}$$

$$Copper\,loss = 0.003141\,Q_{50} + 0.03505, \tag{7}$$

where, $Core\,loss$ is the core loss of 50 Hz transformer in (kW), $Copper\,loss$ is copper loss of 50 Hz transformer in (kW), Q_{50} is the rating of 50 Hz transformer in (MVA).

Equation (6) and Eq. (7) give the loss for 50 Hz transformer, they are combined with Eq. (5) to get frequency-based loss model as Eq. (8):

$$\begin{aligned} Loss_T(f) = 0.0004253\left(\frac{50Q}{f}\right) + \\ +0.003877 + 0.003141\left(\frac{50Q}{f}\right) + 0.03505, \end{aligned} \tag{8}$$

where, $Loss_T$ is total power loss for f Hz transformer in (kW).

4.3. Cable Cost

Cost of AC submarine cable for different power rating has been obtained from reference [28] as given in Eq. (9):

$$Cost_C = A + B \cdot \exp\left(\frac{\sqrt{3} \cdot C \cdot U_{rated} \cdot I_{rated}}{10^8}\right), \quad (9)$$

where, $Cost_C$ is cost of cable in (SEK·km^{-1}), U_{rated} is line-to-line volatage in (Volts), I_{rated} is line current in (Amps), A,B,C are cable constants as given in Tab. 2:

Tab. 2: A, B, C cost parameters.

Rated voltage (kV)	A (10^6)	B (10^6)	C
22	0.284	0.583	6.15
33	0.411	0.596	4.1
45	0.516	0.612	3
66	0.688	0.625	2.05
132	1.971	0.209	1.66
220	3.181	0.11	1.16

Here A, B, C parameters for high voltages ($>$ 220 kV) are derived using the extrapolation technique.

4.4. Cable Power Loss

Ohmic and Dielectric loss which are prominent in the submarine cable is computed using Eq. (10) and Eq. (11):

$$Loss_o = 3\int_0^L I^2(l) \cdot R \cdot dl, \quad (10)$$

$$Loss_d = 3\int_0^L V^2(l) \cdot R_in \cdot dl, \quad (11)$$

where, $Loss_o$ is the ohmic loss in (watts), $Loss_d$ is the dielectric loss in (watts), I is the current along the cable in (A·km^{-1}), R is the resistance of the cable in (Ω), V is the voltage along the cable in (V·km^{-1}), R_{in} is the insulation resistance in (Ω), L is the length of the cable in (km). Here, the current and voltage profile along the cable is computed using Newton Raphson Load Flow Algorithm (NRLFA).

4.5. Cost and Loss of Reactive Power Compensator

Generally, the capacitive effect is predominant in submarine cable, so inductive compensators are required to absorb reactive power generated by the cable. Here Thyristor Switched Reactor (TSR) compensators are provided at either end of the cable. The rating of each of the compensators is taken as half the reactive power generated by the cable. It is computed using Newton Raphson Load Flow Algorithm. Since PTN is long-distance, compensators are only provided for this. The compensator's cost is assumed as $\frac{1}{3}^{\text{rd}}$ of the cost of the transformer of equivalent compensator rating [28]. It is to be noted that reactive power is computed giving due consideration to frequency and need not be mapped for optimum frequency operation while estimating the cost of the compensator. Operational loss in TSR is very less [30], so it is neglected.

4.6. Converter Cost and Loss

The VSC-based DC-link power converter is the present state of the art. Despite being costly it meets the grid code requirements of voltage and reactive power control. The cost of the converter is assumed as 1 SEK·VA^{-1} [28]. The rating of the converter is assumed to be 10 % more than the capacity of the PTN. Operational power loss in the converter is assumed as 2 % of its rating.

5. Results and Discussions

5.1. Test Systems for Case Study

Tab. 3: Configuration details for 200, 400, 600, and 800 MW wind farms.

Wind turbine rating (MW)	No. of turbines per string	No. of strings	Wind farm capacity (MW)
2	10	10	200
2	10	20	400
3	10	20	600
4	10	20	800

Tab. 4: Configuration details for 200, 400, 600, 800 MW wind farms.

Unit rate (€·kWh^{-1})	13
Yearly increase in energy prices (%)	0.15
Interest rate (%)	4
Life span (years)	25

Since the first offshore wind farm was installed in Denmark, the offshore wind turbine size has grown significantly with 12 MW wind turbine being the present state-of-the-art device. The next-generation offshore wind turbine size would be around 20 MW with 275 m rotor diameter by 2030 [1]. Moreover, new GW-scale projects have been announced recently: 2000 MW in Japan, 1000 MW in South Korea, Norway, United Kingdom, and 750 MW in France. So, keeping in view future scale; wind farm capacities of 200, 400, 600, and

Tab. 5: Design of ES for 200 MW OWF (for 50 km offshore distance).

Freq.	Internal distribution network					Power transmission network											
	(1a)	(2a)	(3a)	(4a)	(5a)	(1b)	(2b)	(3b)	(4b)	(5b)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
10	3	20	400	131.7	9.9	3	150	800	26.5	0.7	21.6	7.8	2.2	4	0.2	21.34	−4058
$\frac{50}{3}$	3	20	400	131.7	9.9	3	150	1000	29.8	0.6	19.6	6.2	1.7	2.4	0.2	21.34	−3467
20	3	20	400	131.7	9.9	3	150	1000	29.8	0.6	19	5.9	1.5	2	0.2	21.34	−3328
25	3	20	400	131.7	10	3	150	1000	29.8	0.6	18.5	5.5	1.4	1.6	0.2	21.34	−3191
30	3	20	400	131.7	10	3	150	1000	29.8	0.6	18.2	5.2	1.3	1.3	0.2	21.34	−3102
35	3	20	400	131.7	10	3	150	1000	29.8	0.6	18	5	1.2	1.2	0.2	21.34	−3042
40	3	20	400	131.7	10	3	150	1000	29.8	0.7	17.8	4.9	1.1	1	0.2	21.34	−2999
45	3	20	400	131.7	10.1	3	220	500	24.7	0.7	17.6	4.8	1	0.9	0.3	21.34	−2970
50	3	20	400	131.7	10.1	3	220	500	24.7	0.7	17.5	4.7	1	0.8	0.3	NA	−2951

Tab. 6: Design of ES for 200 MW OWF (for 100 km offshore distance).

Freq.	Internal distribution network					Power transmission network											
	(1a)	(2a)	(3a)	(4a)	(5a)	(1b)	(2b)	(3b)	(4b)	(5b)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
10	3	20	400	131.7	9.9	3	150	1000	59.6	1.2	21.6	7.8	2.2	4	0.4	21.34	−4143
$\frac{50}{3}$	3	20	400	131.7	9.9	3	150	1000	59.6	1.3	19.6	6.2	1.7	2.4	0.4	21.34	−3589
20	3	20	400	131.7	9.9	3	150	1000	59.6	1.3	19	5.9	1.5	2	0.4	21.34	−3455
25	3	20	400	131.7	10	3	220	500	49.5	1.4	18.5	5.5	1.4	1.6	0.4	21.34	−3362
30	3	20	400	131.7	10	3	220	500	49.5	1.6	18.2	5.2	1.3	1.3	0.4	21.34	−3270
35	3	20	400	131.7	10	1	220	500	97.6	1.7	18	5	1.2	1.2	1.3	21.34	−3237
40	3	20	400	131.7	10	1	400	800	345.6	2.1	17.8	4.9	1.1	1	1.3	21.34	−3263
45	3	20	400	131.7	10.1	1	400	800	345.6	2.6	17.6	4.8	1	0.9	1.3	21.34	−3322
50	3	20	400	131.7	10.1	1	400	800	345.6	3.2	17.5	4.7	1	0.8	1.3	NA	−3400

Tab. 7: Design of ES for 200 MW OWF (for 150 km offshore distance).

Freq.	Internal distribution network					Power transmission network											
	(1a)	(2a)	(3a)	(4a)	(5a)	(1b)	(2b)	(3b)	(4b)	(5b)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
10	3	20	400	132	10	3	150	1000	89	2	22	8	2	4	0	21.34	−4265
$\frac{50}{3}$	3	20	400	132	10	3	220	500	74	2	20	6	2	2	1	21.34	−3744
20	3	20	400	132	10	3	220	500	74	2	19	6	2	2	1	21.34	−3641
25	3	20	400	132	10	1	400	800	518	3	19	5	1	2	2	21.34	−3591
30	3	20	400	132	10	1	400	800	518	4	18	5	1	1	2	21.34	−3700
35	3	20	400	132	10	1	400	800	518	5	18	5	1	1	2	21.34	−3848
40	3	20	400	132	10	1	400	1000	779	5	18	5	1	1	2	21.34	−3843
45	3	20	400	132	10	1	400	1000	779	6	18	5	1	1	2	21.34	−4058
50	3	20	400	132	10	1	330	1000	779	7	18	5	1	1	2	NA	−3966

800 MW are considered as test cases. The configuration details for the test wind farms are given in Tab. 3.

The horizontal/vertical distance between wind turbines is assumed as 1 km. Distance from the string to the offshore substation is assumed as 50 km. The economic data such as unit rate, rate of interest, escalation rate, and life span are referenced from [28] as given in Tab. 4.

For the test cases, electric systems are designed for varying offshore distances. The results obtained are as follows.

5.2. Design for ES

Based on the methodology as discussed in Sec. 3. and Sec. 4. , code is written in MATLAB, and it is executed for the test systems. Table 5, Tab. 6, Tab. 7 and Tab. 8 give the design for ES for 200 MW OWF for various offshore distances. The optimum design that corresponds to maximum Net Present Value (NPV) is indicated by yellow shadings. For 50 km offshore distance, optimum operational frequency is obtained as 50 Hz, IDN involves: 3-core, 20 kV, 400 sq. mm cable, PTN involves: 3-core, 220 kV, 500 sq. mm cable, etc. Similarly, for 100, 150, and 200 km offshore distances, optimum operational frequencies are obtained as 35, 25, and $\frac{50}{3}$ Hz respectively. Figure 3 shows the optimization results for different offshore distances.

The results comply with the fundamental intuition that the operational frequency for power transmission decreases with the distance. From the foregoing results it can be verified that optimum operational frequency is an inherent characteristic of the trade-off between investment and operational cost of the ES.

5.3. Economic Feasibility of OFAC

The proposed design is economically compared with HVAC and LFAC. Figure 4 shows the feasible range for

Tab. 8: Design of ES for 200 MW OWF (for 200 km offshore distance).

Freq.	Internal distribution network					Power transmission network											
	(1a)	(2a)	(3a)	(4a)	(5a)	(1b)	(2b)	(3b)	(4b)	(5b)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
10	3	20	400	132	10	3	150	1000	119	3	22	8	2	4	1	21.34	−4400
$\frac{50}{3}$	3	20	400	132	10	1	220	500	195	3	20	6	2	2	1	21.34	−3961
20	3	20	400	132	10	1	400	800	691	4	19	6	2	2	2	21.34	−3983
25	3	20	400	132	10	1	400	1000	750	6	19	5	1	2	2	21.34	−4233
30	3	20	400	132	10	1	400	1000	750	7	18	5	1	1	3	21.34	−4272
35	3	20	400	132	10	1	330	1200	1200	7	18	5	1	1	2	21.34	−4260
40	3	20	400	132	10	1	330	1200	1200	10	18	5	1	1	2	21.34	−4606
45	3	20	400	132	10	1	275	1400	1525	9	18	5	1	1	2	21.34	−4546
50	3	20	400	132	10	1	220	1600	1750	8	18	5	1	1	1	NA	−4352

Internal distribution Network: (1a) - Core no., (2a) - Voltage (kV), (3a) - size of cable (sq.mm), (4a) - cost of cable (M€, (5a) - loss of cable (MW).

Power transmission network: (1b) - core no., (2b) - voltage (kV), (3b) - size of cable (sq.mm), (4b) - cost of cable (M€), (5b) - loss of cable (MW), (6) - cost inter-farm transformer (M€), (7) - loss of inter-farm transformer (MW), (8) - cost of transmission transformer (M€), (9) - loss of transmission transformer (MW), (10) - cost of compensator, (11) - cost of converter (M€), (12) - net present value (T€).

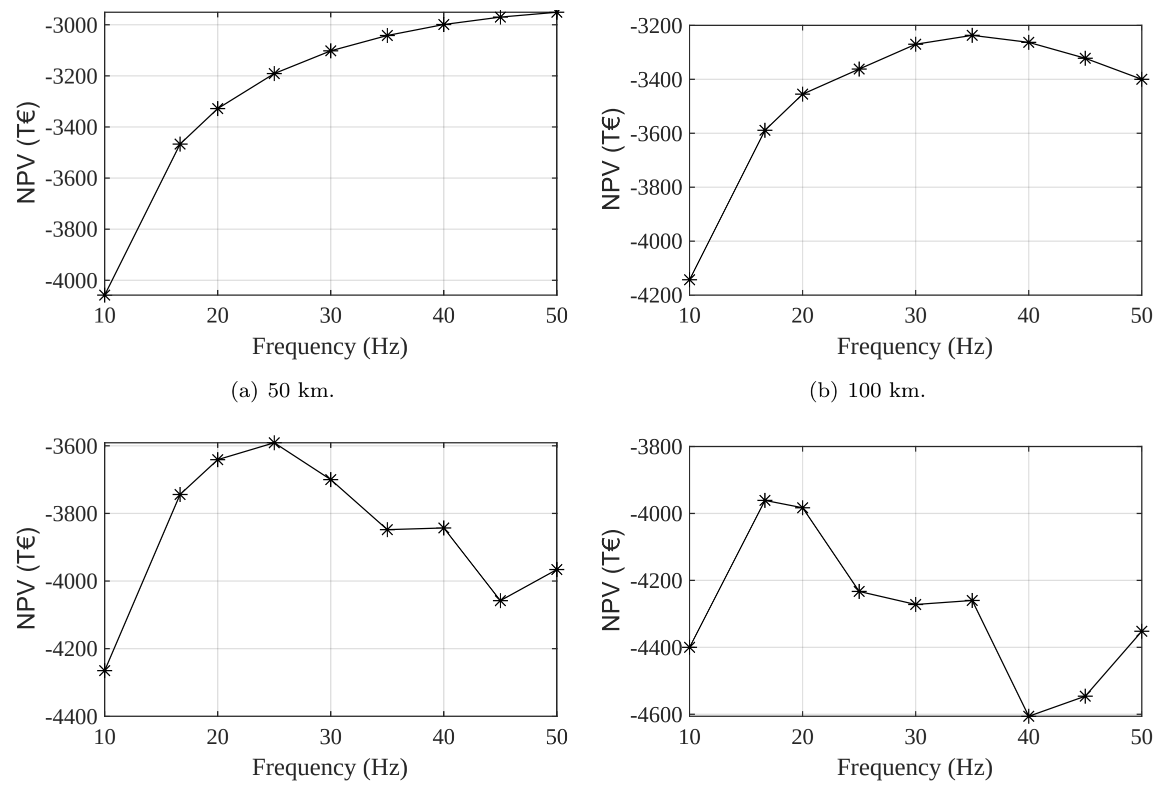

Fig. 3: NPVs with respect to frequency for different offshore distance (200 MW OWF).

HVAC, LFAC, and OFAC for 200 MW OWF. It can be seen that up to 70 km HVAC is feasible, then OFAC is feasible for 70 to 200 km, and beyond that LFAC indicates its feasibility. For 70–200 km, the results clearly indicate that OFAC gives significant savings in the cost of the ES.

Figure 5 shows the saving ensued from OFAC. It clearly indicates that, for 200 MW OWF, OFAC is feasible for transmission length between 100 to 150 km, and it provides a saving of about 5 to 10 % in comparison to HVAC and LFAC. A similar study has been carried out for 400 MW OWF. Figure 6 shows the feasible range of deployment for HVAC, OFAC, and LFAC. Figure 7 shows the saving ensued from OFAC in comparison to HVAC and LFAC. It can be seen that for OFAC, the feasible range is 70 to 130 km, and it provides a saving of about 7 to 10 % in comparison to HVAC and LFAC.

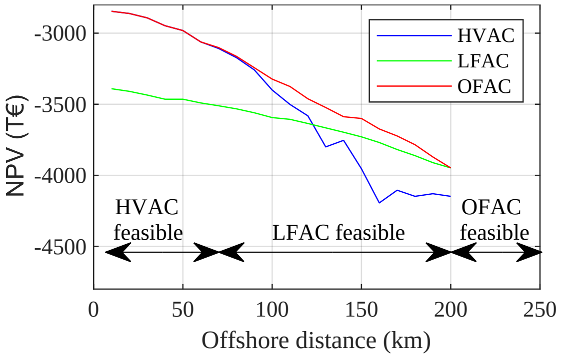

Fig. 4: Economic feasibility of HVAC, LFAC and OFAC for 200 MW OWF.

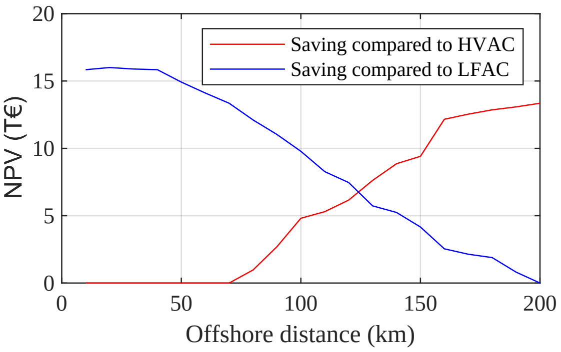

Fig. 5: Savings from OFAC in comparison to HVAC and LFAC for 200 MW OWF.

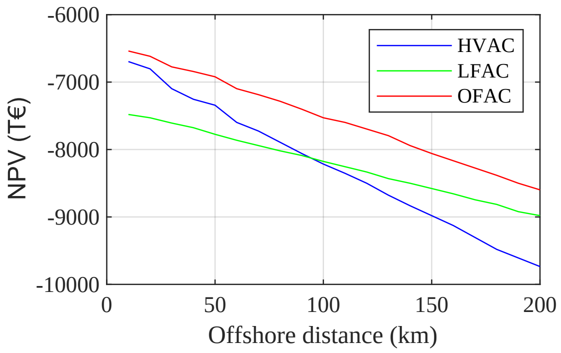

Fig. 6: Economic feasibility of HVAC, LFAC and OFAC for 400 MW OWF.

Table 6 gives the range of feasibility and savings from OFAC for the test cases. It can be concluded that OFAC gives a substantial amount of saving for large-size wind farms and its range of feasibility decreases with the wind farm capacity.

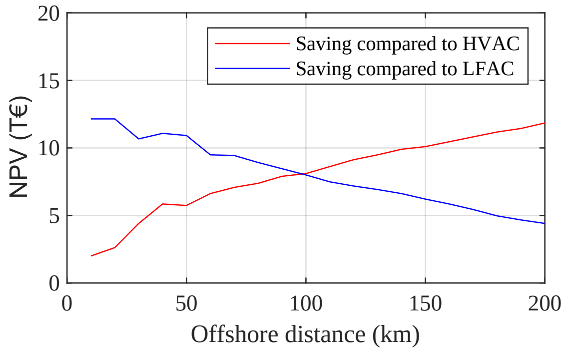

Fig. 7: Saving from OFAC in comparison to HVAC and LFAC for 400 MW OWF.

Tab. 9: Feasibility of OFAC in comparison to HVAC and LFAC.

Wind farm capacity (MW)	Range of feasibility (km)	Saving (%)
200	100–150	5–10
400	70–130	7–10
600	60–110	8–12
800	50–100	9–14

6. Conclusion

The paper has presented a novel methodology for the design of an ES based on optimum frequency considering practical constraints imposed by the standard rating of components. The Structure of the ES for fractional frequency operation has been outlined using a TYPE-IV wind turbine and frequency converter. Models for mapping cost/loss of 50 Hz components for fractional frequency operation have been developed. The results of optimization on the test systems show that a significant amount of saving in the investment and operational cost can be achieved by the proposed OFAC in comparison to LFAC and HVAC for moderate transmission length. For example, the optimum frequency operation for 200 MW OWF shall provide 5–10 % savings in the total project cost. The results further show that savings get enhanced for large-capacity wind farms.

The work presented opens a new dimension for planning/designing a cost-effective Electrical System for integrating OWF into the onshore grid. The proposed technique will aid in promoting the investors to show interest in the development of OWPP. The work indirectly addresses the issues related to dependency on fossil fuels and the economic instability due to fuel price volatility. Further, it also addresses the issues of air pollution and global warming which are the major concerns of the world today in the endeavor.

Power generation at any desired fractional frequency is prerequisite for the success of the OFAC. Further response of protection system under fractional frequency operation is also utmost important. These studies can be extended in the future work.

Author Contributions

U.S.S. contributed substantially to the development of the concept of optimum frequency, the development of methodology for the design of Electric systems, and simulation in MATLAB for analysis and interpretations. Both U.S.S. and D.R.J. contributed to the final version of the manuscript. D.R.J. supervised the work. Both U.S.S. and D.R.J. agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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