Wind Power Plant Substation and Collector System Redundancy, Reliability, and Economics

IEEE PES Wind Plant Collector System Design Working Group

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***Abstract*—This paper presents basic guidelines on design considerations for wind power plant substation and collector system based on redundancy, reliability, and economics. Design considerations, although similar to utility substation and underground or overhead distribution systems, often include aspects not normally considered for those systems. This paper will highlight design considerations unique to wind power plant design comparing economic and reliability benefits among available design options. Power loss analysis in a typical wind power plant is explained. Finally, an overall economic analysis to be considered when designing a new wind power plant is presented.**

***Index Terms*—collector, economics, losses, reliability, substation, wind power plant, wind turbine generator.**

I. Introduction

Conventional utility design practices for substations and distribution systems are typically very different than the those applied for the medium-voltage collector system, collector and/or interconnect substation, and high-voltage transmission line of a wind power plant (WPP). This is due to substantial differences in purpose and economics of these two respective applications. For example, the economic incentives for a WPP are measured by availability, while utility designs focus on reliability, which often requires increased levels of redundancy. Due to incentives, such as the Federal Production Tax Credit (PTC) in the United States, provided for WPP production the economic penalties of inefficiency in a WPP are often substantially greater than those applied to a typical utility application. In contrast to conventional thermal/nuclear power plants, an off-line WPP can return back on-line in much less time; it also has the advantage of operating at partial power output levels based on individual wind turbine generator (WTG) availability.

To optimize an electrical system design for a WPP, the life-cycle cost implications of various aspects such as lost availability, full load losses, and no-load losses must be considered. As discussed in [1], three economic factors condense the complexities of the WPP business model into a form that can be conveniently used in simple spreadsheet calculations to optimize electrical system design for maximized profitability. These factors can be determined from the unique economic characteristics of the specific project, including wind regime, cost of money, tax treatment, and expected project return on investment.

This paper presents basic guidelines on the optimal design of WPP collector and/or interconnect substation that balances redundancy, reliability, and economic considerations. This paper covers only onshore WPPs.

II. Design Philosophy and Engineering Considerations

A. Design Philosophy

Utility substation and infrastructure designs focus on maintaining continuous power flow and thus reliability. This design philosophy translates to redundancy and automatic transfer concepts that recognize faults, clear them as fast as possible, and reconfigure the system appropriately to ensure service continuity. Designs for increased reliability require large initial capital investments, increase the land area required for the design, and can increase system losses and complexity. These initial investments are justified by the value of uninterrupted service to the utility consumers. Since disruptions as brief as a few cycles can result in significant production losses in manufacturing operations [2], the higher cost of the reliability design is justified by the increased continuity of service.

The variability of the wind forces the WPP to operate as a source of energy, with a limited capacity value. Thus, the requirements for service continuity and reliability are not as critical as in the utility system design. However, the value of "green" power is increasing and WPPs are now the most significant contributors to "green" power production targets. In addition to this significant requirement, the WPP infrastructure must be designed to efficiently deliver energy. Thus, consideration of economics and availability are more critical in the design. A WPP requires auxiliary power for WTG heaters, fan, auxiliary motors, and transformer no-load losses when the WPP is not producing power due to wind unavailability; the WPP will need to buy power from the utility at a rate which may be higher the purchased power rate.

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B. Design Considerations

The design of a WPP depends on a number of different design considerations, including:

- The cost and availability of physical space.
- Interconnect requirements for metering and protection.
- The optimal layout of the WTGs, taking into consideration the terrain with the objective of minimizing the potential interaction between adjacent WTGs that can result in reducing the wind energy captured by the individual turbines.
- The type of trenching used for the collector system.
- The soil thermal and electrical resistivity.
- Meteorological factors such as temperature, humidity, possibility of ice and snow accumulation.
- The outcomes of engineering design studies such as load-flow and short circuit analysis.

The details of some of these design considerations are discussed in a companion Working Group paper [3]. The remaining sections of this paper focus on the reliability and economic aspects of the WPP design.

III. Substation Design

Collector substation(s) for WPPs typically use an open-air buswork design with single bus or sectionalized bus arrangements. The latter design is typical for large WPPs (typically 80 MW or larger.) The single bus design shown in Figure 1 is simple and has the lowest overall cost, but has the lowest reliability. The sectionalized bus arrangement shown in Figure 2 enables continued availability when one transformer is out of service. The economic value of the redundancy offered by the second transformer can be evaluated by considering the value of the increased energy production through the life of the WPP. A detailed example of redundant transformer evaluation is given in [1].

The design of the interconnect substation, if separate from the collector substation, is largely dictated by the interconnect requirements. The simplest design can be a pole-mounted disconnect for a small WPP. A more typical design for larger WPPs not involving an additional transformation is shown in Figure 3. In some cases, a ring bus arrangement as shown in Figure 4 is required for reliability at the point of interconnect. For WPPs where a second transformation of voltages occur (typically for interconnection voltages of 345 kV and above), a single bus design is typical.

There are six different bus configurations for consideration when designing the substation of a new WPP. Table I compares the cost and reliability associated with each, noting that three of these would apply to medium-voltage buswork. It is apparent that the double breaker-double bus and breaker-and-a-half configurations have the highest reliability, but also have the highest cost. The configurations that are utilized in the medium-voltage bus design have relatively low reliability compared to the more complicated buswork. Due to the substation transformer rating, it is hard to justify the more complex buswork such as the high reliability bus types listed in Table I.

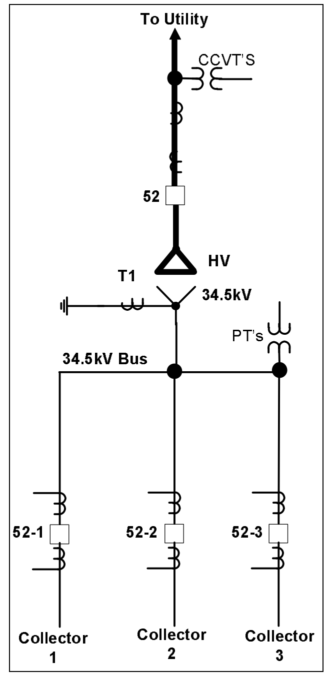

Fig. 1. Single bus arrangement.

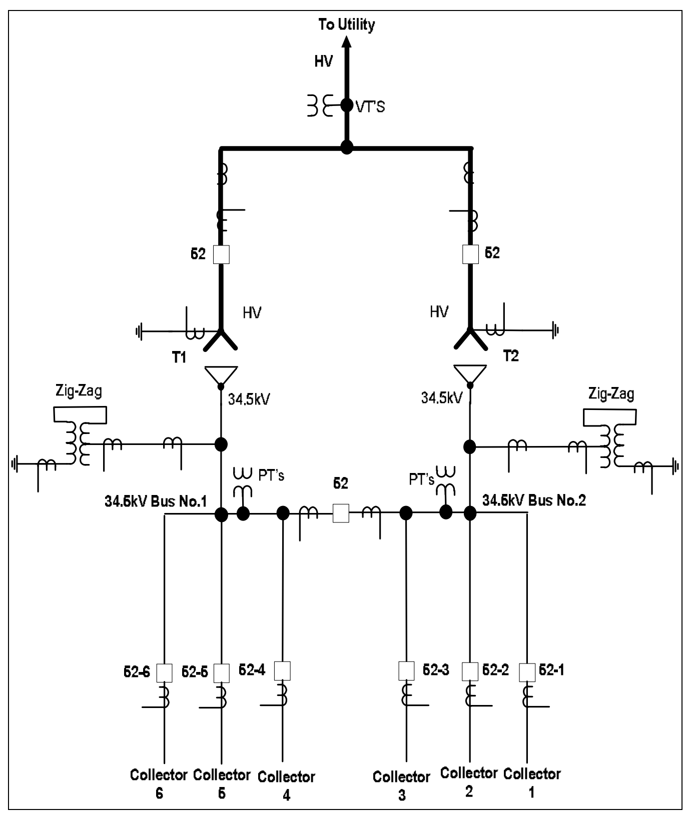

Fig. 2. Sectionalized bus arrangement.

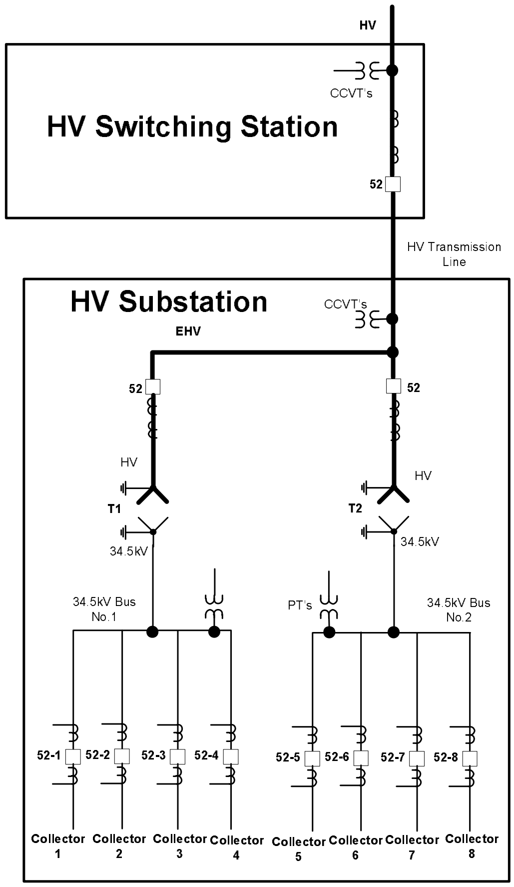

Fig. 3. Typical interconnect substation arrangement.

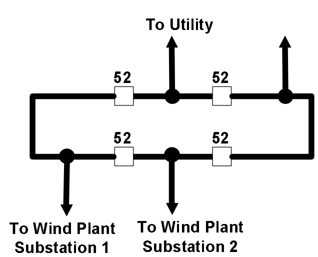

Fig. 4. Ring bus arrangement for interconnect substation.

Table I. Cost/Reliability Comparison for different Bus Configurations.

Bus Type	Cost	Reliability	HV	MV
Single	46.7%	Low	X	X
Sectionalized	57.0%	Low	X	X
Main & Transfer	66.8%	Low	X	X
Ring	53.3%	Medium	X	
Breaker-and-a-Half	73.8%	High	X	
Double Breaker – Double Bus	100%	High	X	

IV. Collector System Design

The length of cable in each section of the collector system is dictated by the layout of the WTGs, the terrain, and access roads in the WPP. The cable sizing is typically dictated by the thermal resistivity (rho) of the soil, ampacity requirements, short-circuit withstand requirements, and conductor arrangement in the trench. The collector system typically represents the largest portion of the total WPP losses. Cable sizing can be optimized to minimize losses by considering the impact of load losses for a particular conductor size [1]. The economic value of sectionalizing collector feeders through the use of sectionalizing switchgear must be evaluated before implementing in the collector design.

V. Wind Power Plant Loss Consideration

The WPP economic evaluation involves consideration of the economic impact of various electrical losses in the WPP. . There are two different approaches commonly used in evaluation of WPP collector losses during design: (1) optimized design where the costs of loss reduction are traded off with the revenue gains realized, and (2) design to a fixed, arbitrary loss goal. Where the latter practice is utilized, typical collector system loss targets are on the order of 2% to 3%. The optimized approach can realize very substantial incremental investment returns for long-term WPP owners.

Estimated total electrical losses in WPP are usually calculated and reported in one of two ways:

- Based on the rated output of the WPP, i.e., losses are expressed as a percentage of the rated output (in MW) of the WPP.
- Based on the annual total energy losses in the WPP, i.e., losses are calculated based on an rms equivalent generation level and expressed as a percentage of the annual energy generated by the WPP. The rms equivalent generation level and associated loss factor (defined as the ratio of the average losses and the losses at rated power) are determined based upon the annual wind speed and power data for the WPP.

The various losses in the WPP include:

- Fixed losses, which do not vary with the WPP production level. These losses include transformer excitation (no-load losses) and conductor dielectric losses.
- Variable load losses, which vary according to the square of output. These losses are due to ohmic losses in cables and transformers.

A. Collector system losses

Collector system losses are typically determined based on the rated output of the individual WTGs operating at a specified power factor and the schedule of cable sizes and lengths indicated in the collector system design drawings. Annual energy losses are determined based on the loss factor and the total number of annual hours.

B. WTG step-up transformer losses

WTG step-up transformer losses are determined based on the no-load and load losses reported in the transformer test report or from representative data for the type and size of transformer involved. If the transformer is operated at less than rated kVA, the energy losses are adjusted by the square of the ratio of the operating kVA and the rated kVA. Annual energy losses are determined based on the loss factor and the total number of annual hours. Due to the high value of the wind generation, and various U.S. tax code provisions, there is a strong incentive for WPP owners to select transformers based on economic loss evaluation. The low loss factor of WPP applications, and provisions that may require the WPP to procure no-load losses during no-wind conditions at unfavorable (e.g., retail) rates, increases the relative importance of no-load losses. For this reason, a number of major WPP developers are now procuring transformers with very low-loss amorphous metal cores.

C. Feeder and substation grounding transformer losses

Feeder and substation grounding transformer losses are also based on no-load losses from transformer test data or representative loss data. Annual energy losses are determined based on the total number of annual hours.

D. Collector and/or interconnect substation transformer losses

Collector and/or interconnect substation transformer losses are based on no-load losses from transformer test data or representative loss data. If the transformer is operated at less than rated MVA, the energy losses are adjusted by the square of the ratio of the operating MVA and the rated MVA. Losses associated with cooling fans are also estimated for various stages of cooling. Annual energy losses are determined based on loss factor and the total number of annual hours.

E. Reactive power compensation system losses

Reactive power compensation system losses are estimated based on representative no-load and load losses associated with the type of reactive power compensation system. For hybrid systems consisting of a dynamic reactive power compensator and mechanically-switched capacitors and reactors, losses associated with the various components must be considered separately. Assumptions must be made on the expected total ON duration for capacitor banks and reactors and the average reactive power output level of the dynamic compensator. Other technologies, such as static var compensators (SVCs) will have different components with losses similar to that of a hybrid reactive power compensation system.

F. Forced Loss of Energy Production

Another loss component not generally considered in the loss calculations for the WPP is the loss of energy due to unavailability of electrical equipment. This would include loss in energy production due to loss of, for example, a WTG transformer or cable failure. Representative loss calculations are explained in [1].

VI. Overall Economic Evaluation of Wind Power Plant

Based on the established economic evaluation process in [4], utility planning should be performed in an incremental cost evaluation. When this principal is applied in WPP economic evaluation, especially for existing plants, the capital investment to reduce the next per unit losses should be justified by the savings from reduced losses. This can be further classified to two factors in utility planning process [3]: the A factor for fixed losses and the B factor for the variable losses. Taking the A factor as an example, it means an initial incremental capital investment of $A (after considering amortization, property taxes, insurances, asset depreciation, and desired rate of investment return) will yield the same amount of cost savings from reduced fixed losses. Similarly, the B factor means investment for variable-loss-saving capital investment that reaches the desired investment rate of return.

For a capital investment to reduce either fixed cost or variable cost, it should be justified by the annual savings from the reduced cost. Certainly, if the amortization, property taxes, insurances, and asset depreciation are all considered, the model will be complicated. The A and B factors allow the engineer to be relieved from directly dealing with these financial intricacies while still allowing these details to be fully included in design optimization. Refer to discussion below on how to obtain the A and B factor as a guideline for economic evaluation of projects to reduce losses.

Fixed losses are present at all times. However, the associated cost when the WPP is generating will be different from the cost when the WPP is not generating. When it is generating, the reduced cost is the selling price from the WPP to the grid. As a comparison, when the WPP is not generating, the cost associated with losses should be the purchase price from the grid to the WPP. Based on this guideline, the present worth of net after-tax revenue change (increase) by a 1 kW reduction in fixed loss can be calculated as:

$$PV_{rev} = \left({}^{p}\!/_{a} \right)^{i}_{life} * \left[H_o * C_{ep} + (8760 - H_o) * C_{gw} + C_{dem} \right] * (1 - T) + \left({}^{p}\!/_{a} \right)^{i}_{life\_ptc} * (8760 - H_o) * C_{ptc} \quad (1)$$

where:

H_o	=	Hours per year with no generation
C_{ep}	=	Cost per kWh of purchased energy
C_{ew}	=	Selling price per kWh of wind generation
C_{dem}	=	Demand (capacity) charge for purchased

power per kW_{peak} per year

C_{ptc} = Production tax credit, per kWh of wind generation

life_ptc = Duration of production tax incentive

The present value of capital investment associated with a capital investment A, with consideration of amortization, property taxes, insurance, and the effect of asset depreciation on income taxes can be calculated as:

$$PV_{cap} = A - A*T*\sum_{n=1}^{life}\left[\left(\frac{p}{f}\right)_n^i * D(n)\right] + A\left(\frac{p}{a}\right)_{life}^i *(1-T)*P \quad (2)$$

where:

A = Initial capital investment

T = Income tax rate

$\left(\frac{p}{f}\right)_x^y$ = Present value of a future cash flow in year x using the compound interest rate y

D(n) = Tax depreciation of capital asset in year n

$\left(\frac{p}{a}\right)_x^y$ = Present value of a uniform set of future cash flows from year 1 until year x, at a compound interest rate y

T = Property tax rate

Life = Economic life of WPP desired after-tax return on investment.

Hence, as (1) and (2) should be equal to each other, we can easily find the A factor.

Similarly, we can find the B factor by finding the present value of future net revenues from the capital investment to reduce variable losses and the present value of the capital investment.

The present worth of future net revenues is given by:

$$PV_{rev} = (p/a)_{life}^i \times 8760 \times K_{Loss} \times C_{ew} \times (1-T) + (p/a)_{life}^i \times 8760 \times K_{Loss} \times C_{pte} \quad (3)$$

where K_{loss} is the ratio of average losses divided by the losses at rated production.

The present value of the capital investment B considering depreciation and tax is given by:

$$PV_{cap} = B - B\times T\times\sum_{n=1}^{life}\left[\left(\frac{p}{f}\right)_n^i \times D_n\right] + B\times\left(\frac{p}{a}\right)_{life}^i \times(1-T)\times P \quad (4)$$

where B is the initial capital investment.

The breakeven value of B should make (3) is equal to (4). Then, the B factor can be easily calculated.

It should be noted that from a reliability viewpoint the outage of WPP will lead to some hours without power output. The calculation of the unavailable hours can be a complicated process that is not covered here. However, once the average unavailable hours are calculated, the economic analysis can be performed with an evaluation factor that is derived similarly to the derivation of the A and B factors. Reference [1] provides the details of this unavailability evaluation.

VII. Availability/Reliability Considerations for Wind Power Plants

There are a number of factors that affect reliability and availability. The general formula for availability is MTBF/(MTBF+MTTR), where MTBF is the mean time between failures and MTTR is the mean time to repair. The reciprocal of MTBF is the failure rate.

A redundant system increases the aggregate failure rate of components (called the "logistics failure rate"), but reduces the overall system failure rate. In a WPP, the effect of a failure on production depends on the details of the collector structure, any associated redundancy, and the extent to which the failure affects the individual WTGs and their associated equipments.

The MTTR for an individual component includes several elements:

- Time to discover the failure.
- Time to travel to the site.
- Time to diagnose the cause of failure.
- Time to obtain any needed replacement parts.
- Time to complete and test the repair.

If the WPP has redundancy and can be reconfigured, the process of system "repair" is the reconfiguration. Any failed individual components can be subsequently repaired with less urgency regarding system availability.

The individual element times in the MTTR can be reduced by remote monitoring and control, implemented in a SCADA system. IEC-61400-25 is a standard for control of wind power equipment that extends the IEC-61850 utility automation standard by adding objects found in a WPP. Examples of these objects include attributes and status of the wind turbine rotor, nacelle, yaw, generator, converter, transformer, and the WPP active power, reactive power, and meteorological tower. A summary of benefits of 61850 and 61400-25 can be found in [4].

Condition monitoring of WPP equipment can help identify potential failures before they occur, thereby allowing preventive maintenance to be scheduled and performed. IEC-61400-25-6 supports condition monitoring, primarily of the WTG where vibration is a major indicator of a potential problem.

The value of both redundancy and automation depends on a number of factors:

1. The overall importance of wind power production to the grid. For example, at a penetration in the range of 20% to 30%, a forced outage of all or part of a wind farm is likely to have a more significant effect than it would at 1% penetration. At the lower penetration level, the lost production due to

unavailability of a WPP can be more easily replaced by other generation. At higher penetration levels, it becomes more important to maintain availability of wind power production. It is not surprising that leadership within the IEC working group that developed 61400-25 came from countries, such as Denmark, with higher wind power penetration.

2. The maintenance approach selected. At high penetration the larger number of WTGs, assuming any reasonable MTBF, ensures that at any time some of the WTGs will have failed and require urgent maintenance. Redundancy and automation reduce the urgency of traveling to the site to accomplish restoration. Similarly, condition monitoring allows scheduling of preventive maintenance and routing of associated travel to minimize urgent direct trips.
3. How many WPPs are being managed by the same entity. The more WPPs that are managed by the same entity, the greater likelihood that automation and redundancy will have benefits to that entity.

VIII. References

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