## Abstract

This paper provides a detailed account on reactive power studies for solar and wind farms in the USA. Farms with main power transformers (MPTs) equipped with both on-load tap changers (OLTC) and de-energized tap changers (DETC) are discussed. Voltage control throughout the collection system is discussed. Optimum Capacitor bank sizing is shown. Lastly, farm reactive power capability, known as P-Q capability, is derived.

## Overview

Provides detailed overview of collection system constraints, turbine constraints P-Q constraints, LGIA and whether voltage range is at POI or high side of MPT. Data Entry Requirements.

Independent system operators (ISOs) and transmission system providers (TSOs) require any solar, wind or battery energy storage project to perform a reactive power study before interconnecting to the transmission grid. This is due to the Federal Energy Regulatory Commission (FERC) order no. 827. FERC order no. 827 mandates that all non-synchronous generation projects meet the 0.95 power factor (PF) requirement at the high side of the generator substation, unless ISOs and TSOs establish a different PF range. The voltage range of this PF requirement is set by the individual ISO and TSO and is generally from 1.05 per unit voltage (Vpu) to 0.95 Vpu. The PF has to be dynamic.

The dynamic piece of the PF requirement is interpreted in most areas of the USA as two sub-requirements that must be met simultaneously: the first is a 0.95 PF sub-requirement at the inverter or turbine low voltage terminals; the second is a 0.95 PF sub-requirement to be met at the high side of the generator substation. The 0.95 PF requirement at the low side terminals of the inverter or the turbine means that the MVA nameplate rating of the equipment cannot be use solely for active power (MW) injection, but a some of that MVA has to be reserved for reactive power (MVAr). The 0.95 PF requirement at the high side of the generator can be met with switched shunts, capacitor or reactor banks, since some substantial portion of the MVAr at the inverter or turbine low side terminals gets lost throughout collection.

Any generator substation has one or more main power transformers (MPTs). These MPTs step up the collection system voltage, typically 34.5 kV to the transmission system voltage, typically 138 kV and higher. The inverter or turbine transformers step up the inverter or turbine low side voltage, typically at 0.63-072 kV to the collection system at 34.5 kV. Some areas in the USA interpret the second 0.95 PF sub-requirement as being measured at the low side of the MPTs instead of the high side of the MPTs. Some other areas, notably ERCOT in Texas, interpret the second 0.95 PF sub-requirement as being measured at the POI as they include the tie-line from the MPTs to the transmission grid in the project. Lastly, it should be noted that the exact PF requirement, voltage range and point of measurement is always listed in the interconnection agreement (IA) of any project. In the following, it will be assumed that the PF requirement is being measured at the high side of the MPT for a voltage range of 1.05 Vpu to 0.95 Vpu. As will be seen later, this does not make any difference and any other PF requirement variation can be studied similarly. A typical US renewable project layout is shown in figure %%%

## Data Requirement

Positive sequence data for all project components is required. Majority of collection system is underground and thus cable resistance and reactance along with cable charging capacitance is required. Cables are laid in the ground either in trefoil or flat formation. The cable impedance used should correspond to the formation used. Trefoil configuration has slightly more reactance than flat formation due to the close proximity of the cable conductors. Thus, trefoil configuration produces a bigger capacitor and reactor bank size, if one is required since more reactance means more dynamic MVAr loss across collection system. Typical cable data is given in .

Transformer positive sequence impedance is needed along with no load losses. This is applicable to MPTs, inverter step up transformers (ISU) and wind turbine transformers (WTTs). Most of the times, the project is designed before transformer test reports are available. Worst case transformer allowance should be used. It is very typical that ISUs and WTTs deviate from their bid data by as much as 7.5% per IEEE %%% standard. This seems to be due to the relatively small MVA size of these transformers. On the other hand, MPT test report impedance deviates slightly from design data. It is safe to assume that the MPT impedance is within 1% of the design data. Being very conservative with MPT impedance can cause substantial MVAr loss across the MPT and leads to a very conservative capacitor or reactor bank size. This is due to the substantially large MPT impedance compared to the PMT. Most MPTs in renewable projects are three winding transformers with the tertiary winding connected in delta and not connected to any external load. Thus, modeling the tertiary winding is not required since no-load losses flows in it which is small compared to the overall losses across the MPT.

The tie-line positive sequence impedance must be included in the project if the tie-line is of substantial length. This becomes critical if the PF requirement is at the POI rather than at the high side of the MPT. A lot of renewable projects are connected to the POI through a short slack span and it is negligible in this case.

Lastly, inverter and turbine reactive power capability (P-Q curve) should be modeled. Care should be exercised when modeling any P-Q voltage dependency during simulations. It is typical that turbines and inverters have P-Q curves that are voltage dependent. Typically, turbine and inverters provide more reactive power as the voltage at their terminal rises. When the voltage exceeds or drops below certain voltage level, typically 1.1 Vpu and 0.9 Vpu, the turbine or inverter capability becomes extremely limited. It is thus important to control the voltage at turbine terminals to rated voltage range to maximize turbine and inverter MVAr contribution. Maximizing turbine and inverter MVAr contribution is necessary to keep the capacitor bank or reactor bank size at minimal size. Voltage control will be detailed in section $$. Two examples of turbine P-Q capability is given in $$$. Two examples of inverter P-Q capability is given in Appendix %%.

It is important to note two points at the P-Q curves of the turbines and inverters: one at maximum active power output, and one at zero active power output. The point at maximum active power output correlates closely the capacitor bank size since the dynamic MVAr loss across collection is maximum. It is rare that a renewable project needs a reactor bank at full power output to meet the PF requirement. The reason for this will be shown in section %%. The zero active power output correlates with the reactor bank size. Some old technologies of turbines and inverters have zero MVAr capability at zero active power output. This leads to some charging MVAr at the high side of the MPT due to cable charging current. Some IAs require that the project offset charging MVAr and in this case a reactor bank is the cheapest solution.

## Adjustment of Tap Changer Settings

This section discussed the main component of the study which is the tap changer settings.

### OLTC Settings

Copy from NFR or TGE

### DETC Settings

Copy from PacifiCorp

## Capacitor bank sizing

Talk about adding steps and flicker

## P-Q Capability