VOLTAGE CONTROL GRID CONNECTION REQUIREMENTS FOR RENEWABLE POWER PLANTS CONNECTED TO THE ELECTRICITY TRANSMISSION SYSTEM IN NIGERIA

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***Abstract*—Upcoming construction proposals for utility-scale photovoltaic plants and discussion of compensation in Nigeria raise the question of appropriate grid code requirements to support system voltage control objectives. The large geographical extent, long lines, and small number of generators in the Nigerian High Voltage System make voltage control a critical issue. This paper evaluates the effect of different power control strategies for a 100 MW solar plant, using dynamic simulation of a detailed grid model. The choice of location in North of Nigeria informs ongoing discussions, and is the first published study of this type. The effect of the strategies are compared, and recommendations are made for transmission system operators and developers to consider as they define interconnection agreements.**

***Keywords*—grid code, power, utility-scale solar farm, surge impedance loading**

I. INTRODUCTION

The employment of renewable energy sources is driving an increase in amount of embedded generation that is connected to the Medium Voltage (MV) and Low Voltage (LV) distribution network. Due to the lower availability of the grid at low voltage, initial proposals for on-grid photovoltaic generation in Nigeria have been lodged for connection to the high voltage network. The peak load in Nigeria is typically not more than 4GW, and load at a given location may be frequently connected and disconnected during the process of manual frequency control directed by the National Control Centre. The Nigerian high voltage transmission system comprises ageing and problematic equipment with long lines, which are typically not loaded up to their surge impedance limit. The power production by these lines necessitates the switching in and out of line reactors to maintain acceptable voltages. Thus connection at high-voltage is a prospect that still requires careful study.

Voltage fluctuations and sudden demand can already cause serious power quality effects [5] in systems with a small number of generators and industrial loads such as Nigeria. Keen interest is present from the Transmission Company of Nigeria to ensure grid-connected photovoltaic plants to maintain and enhance the grid voltage profile as much as is technically possible, while power generation project developers must restrict their participation to what is economically viable. If too many voltage profile issues occur, it can happen that the maximum size of allowable generation plants is limited by the operator. This discussion regarding utility-scale power plants necessarily centres around newly added connection requirements for the specific case of PV generation.

From a generator developer point of viewpoint, Grid Codes are basically a set of technical conditions and requirements to be followed when connecting generators to the grid.By compiling with these rules the power plant ensures system stability when connected to the grid. Grid Codes demands numerous requires numerous requirements that PV systems have to fulfil to facilitate their integration into existing power systems. The requirements may vary depending on the voltage level (high, medium or low) the PV system is connected to, and on the issuing country. One of the major issues associated with PV infeed in distribution networks is voltage rise on feeders violating the allowed limits [2], which in Germany has led to the imposition on PV generation of specific power control schemes [6]. National Grid Codes may require the capability to provide power on all voltage levels, and such schemes are dictated by grid planners and operational specialists based on the specific conditions of their system. In the past, the grid was developed around large synchronous generators typically connected to the transmission system. From the perspective of and voltage power control, utility-scale solar plants share all of the capabilities of synchronous generators, including that of operation as a synchronous condenser even when no active power is being generated. They are however limited more strictly by the rating of their AC power electronics.

This paper addresses the question of what type of power control should be required of utility-scale solar farms connected at high voltage in Nigeria. Well-known schemes of constant power factor control, voltage regulation, and voltage droop are evaluated for a specific and likely location and size of solar farm. A detailed model of part of the Nigerian high voltage grid is used to determine the preferred scheme, and the likely required inverter ratings to ensure compliance with existing voltage range recommendations at relevant voltage levels.

II. Model Description

A. Description of the Nigeria Transmission Network

The transmission network in Nigeria consists of 330kV and 132kV lines, as depicted in Fig. 1. Relatively long lines constrain the voltage profile, and northern substations are lightly loaded, in some cases requiring permanent connection of energizing reactors due to loading below the surge impedance limit. The high voltage system has two known problems: inadequate capacity and a fragile structure that increases the risk of total system collapse if one element fails. The present installed generation capacity of the Nigerian National Grid is approximately 13GW, of which 67 percent is thermal and the balance is hydro-based. By 2016, the transmission network consisted of 6000km of 330-kV lines, and 7000-km of 132-kV lines. The 330kV lines feed 23 substations employing transformer with voltage rating of 330/132-kv with a combined capacity of 6000 MVA. The 132kV lines fed 91 substations employing transformer with a voltage rating of 132/33kV with a combined capacity of 7800MVA. However, total served load is seldom above 4GW due to transmission constraints, gas availability, and various forms of instability.

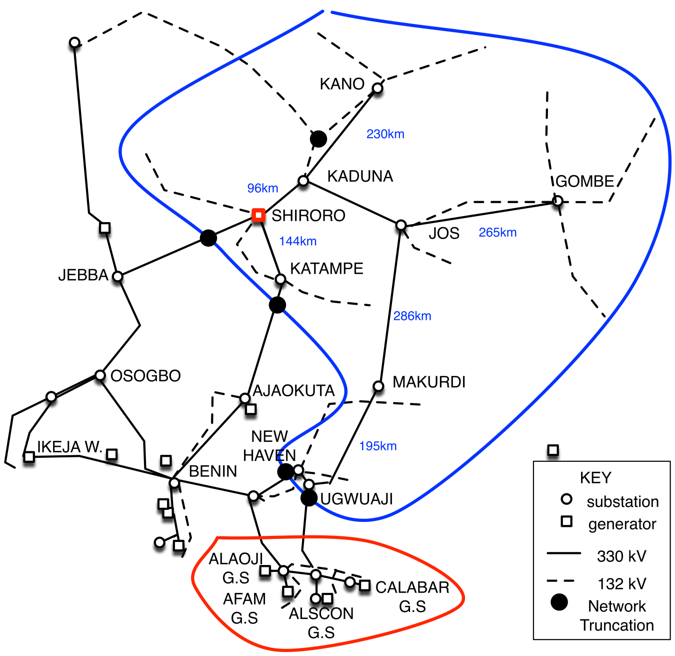


Fig. 1. Transmission network of Nigeria with, with network retained for detailed study marked in blue and strong generation area equivalenced as a voltage source marked in red. Line lengths are labelled in areas of focus.

B. Sub-Network of Interest

Most locations in Nigeria have commercially attractive solar yields, with that of Northern sites being roughly 50% greater. An additional preference for Northern locations stems from the lack of local generation and a need for compensation in its long lines. Likely substations for a utility-scale photovoltaic installations thus include Kano, Kaduna, Jos and Gombe. The portion of the network encircled in blue in Fig. 1 has thus been chosen for closer study, as detailed in Fig. 2. The hydro generation station Shiroro (red square) and south-eastern region (encircled in red) presently supply power, and was included as a slack generator regulating its terminal voltage The Southern export has been represented by equivalencing nearby loads, and approximating the multiple generators that supply the South East by a stiff voltage source. This resulted in realistic balance between long Ugwuaji-Makurdi-Jos line and local loads, and realistic active power export to the North, as observed in practice.

C. Model

Using data provided by the Transmission Company of Nigeria and the Power Holding Company of Nigeria we modelled the current national power system in an EMTP-PSCAD environment and ran various load flow studies under normal conditions. The EMTP-PSCAD environment allowed full modeling of effect of long lines in the network and facilitated modeling of farm control loops. Transformers down to 33kV were represented in the network, where loads at 33kV were aggregated. Transformer loading reports were used to estimate likely loadings. The size and date of non-concurrent peak-loadings are available in these reports and indicate that peaks are uncorrelated. Thus the geometric sum

$$P_{TOT} = \sqrt{\sum_{i=1}^{N} P_i^2} \tag{1}$$

was used to determine a representative total loading. Load power factor in these reports is 0.91 lagging on average, and was used for all loads. Decisions on load modelling and transformer tappings were made to develop a converged case study with acceptable system voltage levels as dictated by grid code, which are tabulated in Table I.

TABLE I. Grid Code Requirements, Transmission Company of Nigeria

Voltage level	Minimum Voltage (PU) kV (pu)	Maximum Voltage (PU) kV (pu)
330 kV	280.5 (0.85)	346.5 (1.05)
132 kV	112.2 (0.85)	145.2 (1.10)
33 kV	31.02 (0.94)	34.98 (1.06)

D. Solar Farm Modelling

The paper examines effects of introducing a collector system typical of a large utility-scale solar farms [4], [1] at a rating of 100MW. Several projects of this size are in discussion with ministry and transmission network officials. In this work, no switching was included. Instead, a phasor model of three current sources was used to approximate a voltage controlled current source control. The sinusoidal output currents with controllable magnitude and phase angle were set using standard dq-frame controls. The one-line diagram shown in Fig. 3 shows the three phase ideal model of three phase current source connected to the grid. The reference frame was calculated using voltage measurement at the point of interconnection. Objectives for the d-axis were defined using active power, while objectives for the q-axis were specified as the output of a PI feedback on power. power was in turn defined according to three options, to explore power control strategies:

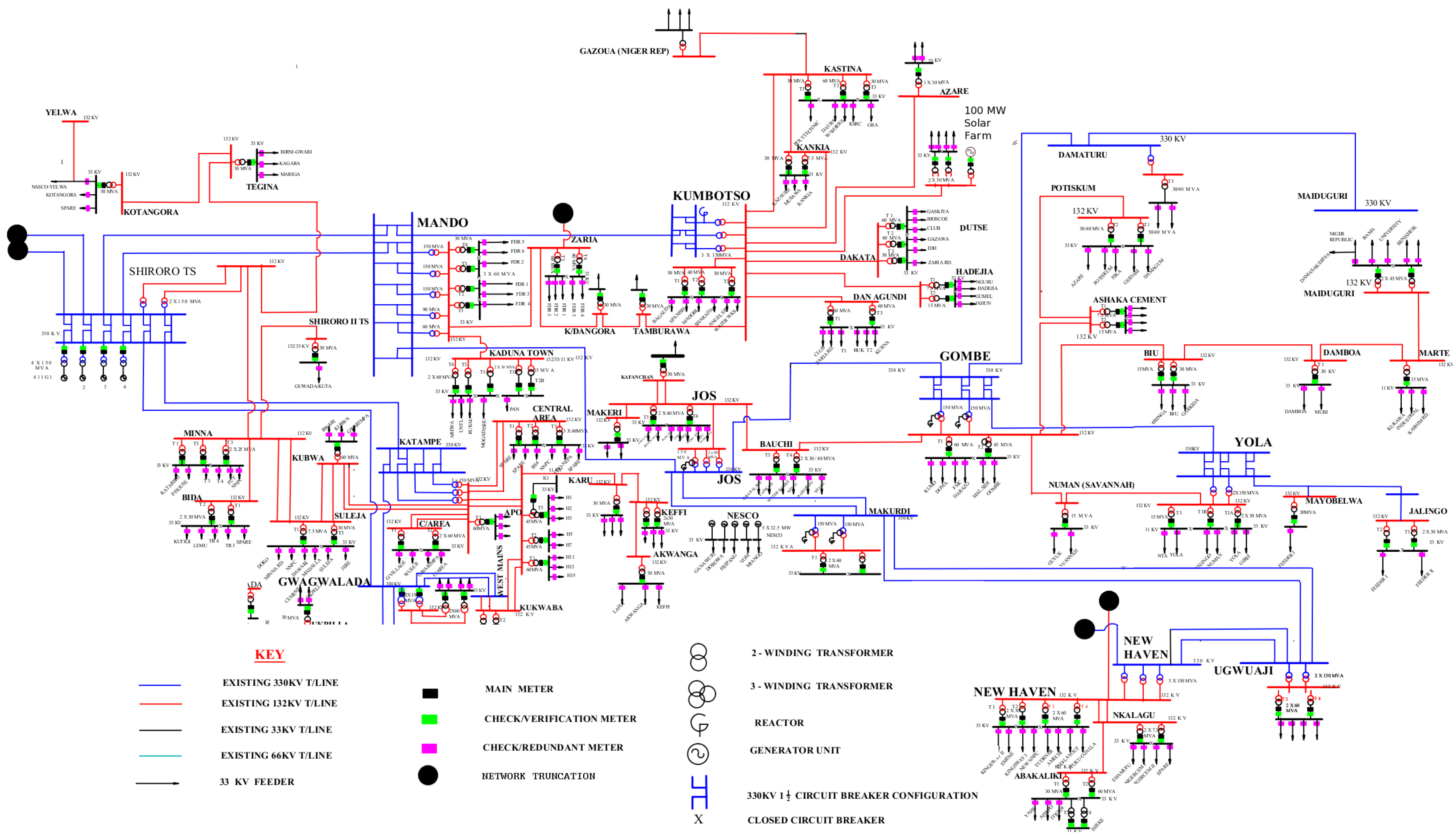


Fig. 2. Network Area of Focus: Detail, showing multiple voltage levels, transformers, and network topology.

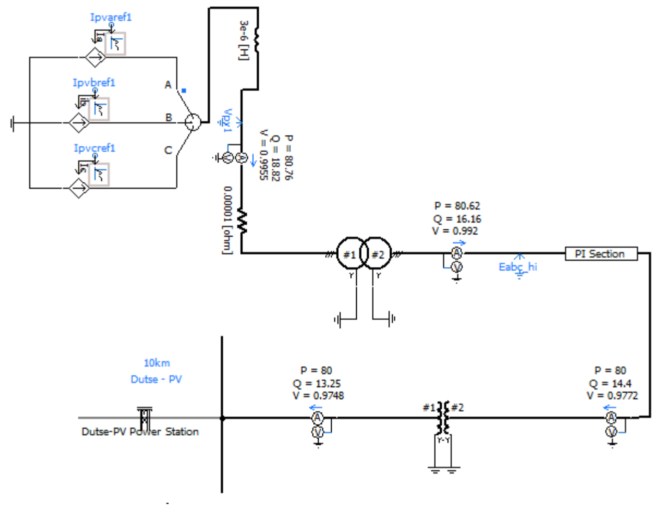


Fig. 3. Single equivalent ideal current source model of solar farm interfaced through collector system.

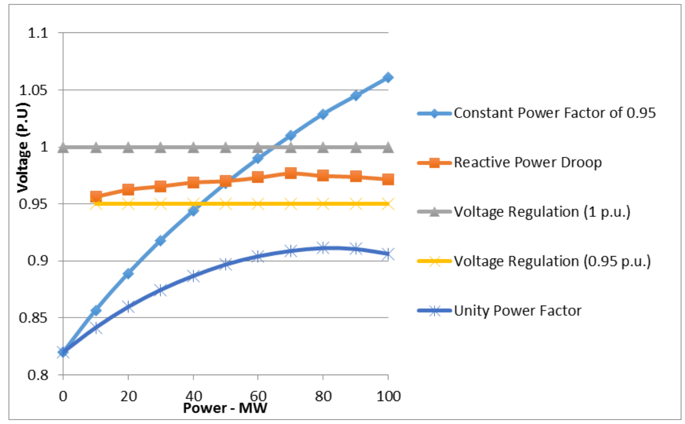
1) Constant power factor: (reference in chosen proportion to active power)
2) Reactive power droop: (reference derived from proportional gain on voltage deviation)
3) Voltage regulation: (reference generated by PI loop driven by voltage setpoint error)

The droop option was calibrated to deliver up to the full rating of the converter when at either grid-code limit as measured at the point of common coupling (PCC).

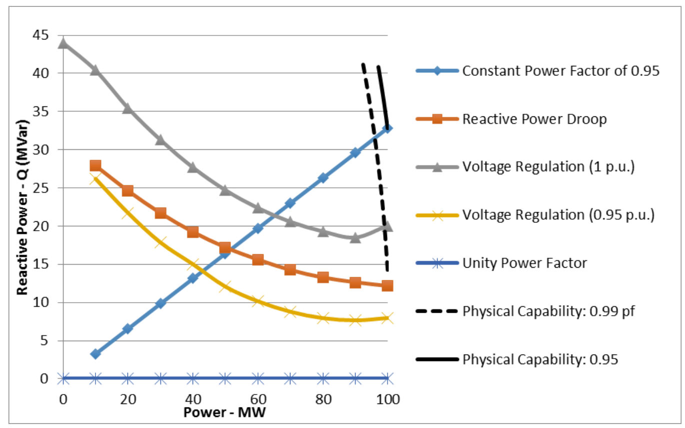
The options studied cover the range seen in practice, and offer different trade-offs of voltage performance. The voltage regulation necessarily demands wide ranges in reactive power, but does deliver a stiff voltage. However, that setpoint must be recommended based on common conditions, and may become inappropriate in systems with wide changes in loading conditions. Also, voltage regulation requires that transients be compensated by the current controls of the inverters. This burden increases some losses and wear and tear. It also introduces the possibility that the converter becomes sporadically and transiently current-limited, leading anyway to voltage fluctuations. The droop method is a distinct choice where only grid code ranges need be specified, and it becomes assured that the converter contributes its utmost current rating only in extreme situations. No setpoint is required. The lack of voltage regulation is the drawback, but voltage movement may provide information to operators. The constant power factor method produces the largest shifts in local voltage, with an adjustable steepness. Being a contribution in proportion to power injected, it provides no grid support at night, and constitutes the least demand on the solar farm. The selection of an exporting power factor does mitigate voltage rise due to active power injection, and can provide some improvement of voltage; however, it may also introduce variability in voltage in sync with slow solar resource fluctuations.

III. Results

In Fig. 4(a), showing the voltage at the point of common coupling, we see that all variants of PV plant control improve the local voltage from its heavy-load (and outside grid code specified) value of 0.85.



(a) Voltage



(b) Power

Fig. 4. Behaviour at point of common coupling (PCC) for different power control strategies. Black curves indicate region of possible power injection for inverters rated to 0.99 and 0.95 import/export power factor.

Operation at constant power factor (blue diamonds) optimally compensates the local voltage when the farm is at half production, but under-contributes for low production (e.g. as at night) and over-contributes power at full production. Thus it has the potential to frequently violate grid code and would provide no power support at night. If constant power factor had to be applied, at least a lower value (perhaps 0.98) would be better, but it is advised not to prescribe or require operation at any constant power factor. The low voltage condition of the bus before adding the solar plant partly explains why the common approach of constant power operation is not sufficient.

Operation for strict voltage regulation was proven to be viable for voltage set points of both 1.0 p.u and 0.95 p.u voltage (gray triangles and yellow crosses). Operation in voltage regulation mode has the advantage of delivering the ideal contribution of power at all times, but carries the disadvantage of producing a voltage that gives no indication of system strain. That is to say, if the power limited is reached, voltage will rapidly decline from the set point with further loading. Operation with a power droop designed to give maximum effort only at grid specified upper and lower limits (orange squares) delivers a less steady voltage profile, but provide an indication to operators of system loading. It may also result in lower losses, though this was not evaluated. As mentioned earlier, the droop method results in a condition-driven contribution present at all times, and most strong when grid code extremes are reached. For the conditions shown, the range of reactive power injected is the smallest of all methods (save the trivial case of unity power factor), giving a compromise between use of the inverter and voltage quality.

Fig. 4(b) indicates the power required by the PV plant at the point of common coupling. The most demanding condition is at full power production of 100MW, because the current capability of the inverter is near its maximum. The black solid and dashed lines (no marker) of Fig. 4(b) indicates that a central inverter rated for 0.95 is ample for all voltage regulation purposes. For plant active power output between 70-100 MW, no more than 20 MVAr is needed, even for 1.0 voltage regulation. As active power drops, ever more inverter current capability becomes available. Thus, even a central inverter rated at 0.98 exporting capability would be physically capable of covering all power needs for 1.0 voltage regulation, and 0.99 would also likely suffice.

It should be noted that many central inverters are sold only with a unity power factor feature, and that the provision of leading and lagging power factor capability must be specified and required for demonstration during commissioning. Actual voltage regulation is also likely to be an additional feature. However, the benefit to the system is substantially greater than the cost incurred to the developer, which should be relatively minor. This cost will be outweighed by the increased permissible connection size of a fully voltage controlled generator.

The validity of these results is highly dependent on the scenario chosen. It is recommended to perform another study where 132kV lines from the eastern axis of Jos and Gombe are included, rather than being represented as lumped loads. It is also advised to consider a low-load case to see whether power import by the PV plant is also sufficient.

IV. Recommendations and Future Work

The results of this study indicate that operation of central inverters of utility-scale solar farms to provide constant power factor operation would be a poor choice in Northern Nigeria. It is recommended instead that either voltage regulation or voltage droop be selected for grid code requirements. In general, practice around the world varies depending on the needs of the particular grid, and the desire of operators to specify setpoints versus specifying plant operation more broadly. The full range of technically possible capabilities should be contemplated [3]. The location examined in this study indicates that fixed capacitors will likely not be necessary for a utility-scale solar plant, as commonly found inverter ratings were sufficient to provide the needed power to meet grid code even at full production.

This paper has evaluated a typical load case. The authors believe the recommendation to use voltage regulation or voltage droop will hold for other cases, due to the need for stable voltage and presence of long lines. However, since other unit commitments and loading cases are known to occur, future work will evaluate lightly loaded cases and scenarios where key generators and lines are out of service. Future work will also determine whether there is a significant difference between voltage regulation and power droop regarding losses.

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