Design and Analysis of 1
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Abstract
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Design and Analysis of 1.5 MVA 25kV Hybrid Traction Feeder Powered by 415kW Solar Grid - Part I

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Abstract—This is a four-part paper series, which elaborates the novel hybrid design where the rated capacity of 415 kW solar power plant producing guaranteed 1.66 MWh per day, owned by a private firm supplies electrical energy to its privately served consumers and also feeds 25 kV railway distribution feeder located 20 Km away from the premises. This 415V transmission is boosted and feeds the lagging feeding post of 40 km long traction line which has hybrid 132 kV/25 kV transmission from DISCOM or Govt. owned substation, supporting train speed upto 160km/hr. These four part paper series are complete guide, enough to motivate investors and successfully demonstrates relay trip coordination, leading the role of one section of feeding post from 132 kV/25kV utility and handling of other safety and fault conditions. In this Part-1, the solar plant design with anti-islanding, guaranteed uninterrupted power supply, typical railway distribution feeder, design of proposed feeder - its connection to feeder, mounting pole, booster transformer, circuit breakers, isolators, lightening arresters, has been explained. The whole proposal is also simulated and the results are in the dataset.

Index Terms—railway system, rail transportation, rail transportation control systems, protective relaying, electrification, 25kV, centralized-decentralized control, traction substation, power quality, energy conservation, 160km/hr.

I. INTRODUCTION

These papers are part of the proposal design (for innovation challenge) proposed by the author, which is modified here with more explanation than was initially submitted in the small concept paper to Ministry of Railways, Govt. of India in the year 2017.

All railway feeders take power supply from state utility. This paper elaborates the novel hybrid design on known concepts with the controller, which is tested using simulation. The biggest challenge in such hybrid design is efficiently leading and switching the load of one section to this distribution feeder, while managing efficient trips in the event of faults or maintainence or during operation.

The paper series are organized as: In this first part, the design of the solar power plant, the guaranteed generation of rated power, MPPT algorithm, anti-islanding, design of typical 25 kV railway distribution feeder from 132 kV State Utility.

The second part of this series comprises

The paper is organized as follows: In the Section II, the design of the solar power plant and the generation of rated power has been explained. The susections - Incremental conductance and anti-islanding discusses the MPPT algorithm and the disconnection of the continued power supply during islanding. In the Section III, the typical 25 kV railway distribution feeder has been discussed in brief with the connection to the solar power plant where the proposed controller would be attached. In the Section IV, the proposed controller design has been explained in subsections -

In the Section V, the conclusion and future work is summarized.

secure and safe guaranteed connection to railway distribution feeder on the 132 kV hybrid transmission is explained, monitoring
II. SOLAR POWER PLANT

Fig. 1 shows the high level block diagram architecture of the power plant supplying electrical energy to its consumers and also feeding the lagging end of the feeding post of the traction distribution feeder.

The solar power plant is privately owned with rated capacity of 415 kW and produces guaranteed minimum 1660 kWh per day, that is 1.66 MWh per day, of which 1510 kW (1.51 MW ≈ 1.5 MVA) would be transferred to the railway feeder and the remaining 150 kWh to its consumers comprising of 150 houses with pre-sanctioned of maximum of 1 kW per house per day. As the 1660 kWh per day is the guaranteed minimum power generation per day, which means the extra generated power will charge battery bank.

In the Fig.1, the arrangement of solar arrays and panels in series and parallel give 415 kW is shown. The solar power is generated in distributed manner, in 4 array system with 4 separate boost converters. Each array initially had same number of modules in series and parallel.

practically, the duty cycle and hence the power output varies according to irradiance W/m² and temperature. In the simulation, it is found that the temperature of 2 arrays reach 45°C, thus, losser power is generated and so more modules are added in the array to make the private solar grid at rated 415 kW.

Array 1 has 32 parallel strings where each string has 5 series connected modules. At 40°C, this generates 48.11567 kW. Array 2 has 32 parallel strings where each string has 5 series connected modules. At 35°C, this generates 48.88365 kW. Array 3 has 32 parallel strings where each string has 5 series connected modules. At 45°C, this generates 47.34275 kW. Array 4 has 32 parallel strings where each string has 5 series connected
modules. At 50°C, this generates 46.56418 kW. Collectively, all this generates 190.90634 kW, which is less than the expected rated capacity of the plant.

So, changing the configuration of Array4 from 32 to 44 parallel strings yields 64.03185 kW at 50°C. Similarly, array2 has 40 parallel strings which yields 59.18235 kW at 45°C. Collectively, this yields 220.21343 kW.

Each solar panel has rating of 300 W with 96 cells connected per module, open circuit voltage, $V_{oc} = 64$ V, Voltage at maximum power point, $V_{MPP} = 54.7$ V, short-circuit current, $I_{sc} = 5.96$ A, current at maximum power point, $I_{MPP} = 5.58$ A. In simulation, the temperature coefficient of $V_{oc}$ and $I_{sc}$ is taken as -0.27269% per °C and 0.06145% per °C respectively.

In the Fig. 1, each of the four arrays have similar configuration. Each array has blocking and bypass diode ‘D’ in series with fuse ‘F’ and circuit breaker ‘c.b.’ with DC disconnect ‘Di’, in parallel with surge arrestor ‘S’. This in turn is boosted with MPPT DC-DC converter. All the outputs of all these four DC-DC converters is connected in series and connected to anti-islanding three level three phase neutral point clamp (NPC) inverter. All the equipments and arrays have been connected to ground pit and also all the arrays are protected using lightening arrestor ‘L.A.’. The output three lines R,Y,B of this inverter is connected in series with fuse ‘F1’ and in parallel with surge arrestor ‘S1’, which is then connected to circuit breaker ‘c.b.’ having feature of thermal overload ‘T’ and magnetic overload ‘M’ protections. This gives both instantaneous and time-delayed protection. The output three phase 440 VAC transmission of this, is divided into two transmission lines, one to feed consumers and the other to power the railway distribution feeder.

The transmission line to consumers is connected to ‘AC Disconnect 2’ with multichannel meter to monitor theft and for prepaid disconnection. This line is further divided into five consumer lines of 415 VAC, where the expected load is approx. 600 kWh per day. Further details are beyond the scope of this paper.

For the testing and simulation purposes (results of which are tabulated in Part-II), the solar photovoltaic (PV) cell is modeled with the known basic one diode model (diode saturation current, $I_s = 6.3014 \times 10^{-12}$ A and ideality factor of 0.94504) with shunt resistance (269.5934 Ω) and series resistance (0.37152 Ω). And the collective voltage and current measurements of all the solar panels is denoted as $V_{solar}$ and $I_{solar}$ respectively.

A. Incremental conductance

The MPPT (Maximum Power Point Tracking) DC-DC boost converter operates at switching frequency of 50 kHz, whose duty cycle is varied according to ‘Incremental Conductance’ algorithm, as explained in flowchart, Fig. 2 (given for completion purposes). The flowchart is based on concept of slope of PV array power curve and is shown only for Array 1, the other three arrays Array 2, Array 3 and Array 4 also implement the same algorithm.
Fig. 2: Incremental conductance

\[
\frac{dP}{dV} \begin{cases} 
= 0 & \text{at MPP} \\
> 0 & \text{at left of MPP} \\
< 0 & \text{at right of MPP} 
\end{cases}
\] (1)

B. Anti-Islanding

Anti-Islanding is a must requirement in such designs, because the proposed controller feeding the part of the 25 kV traction, will go through maintenance numerous times like maintenance of potential or current transformers, oil checking and other scheduled operations. Moreover, to switch from R-Y to Y-B or R-B using the TPST (triple pole single throw) as shown in Fig. 5, the solar power plant must not supply power to this transmission line. During the fixed-scheduled maintenance, such condition is known but at most other times, maintenance on DISCOM owned feeded may be required and the disconnection of the DPST (double pole single throw), shown in Fig. 4 is also must in such cases.

To detect, whether the DISCOM engineer has disconnected the solar plant power supply, that is disconnected the DPST, the voltage and frequency is continuously monitored on this line and if the result deviates from the pre-setting allowed variation, the microcontroller based supervisory circuit sends alarm and SMS to maintenance department of the solar power plant. Fig. 3 shows for both AC disconnects - AC Disconnect 1 and AC Disconnect 2, the transmission lines are monitored using current transformer, which is feeded to ADC (Analog-to-Digital Converter) of the microcontroller, and which calculates and displays, all the voltages, currents and frequency namely \( V_1, V_1, V_1, I_1, I_1, I_1, V_2, V_2, V_2, I_2, I_2, I_2, \text{freq}_1, \text{freq}_2 \), on both the transmission lines.

Here, instead of the use of only two current transformers (c.t.), three c.t. are used to measure all the three phases, to make ensure of phase imbalancing and islanding.

C. Simulation Results

D. guaranteed uninterrupted power supply

guaranteed uninterrupted power supply
Simulation Results The complete proposal has been simulated and the resulting datasets are uploaded on IEEE DataPort, titled as "Data:415kW Solar Grid Powering 25kV Traction" [1]. The results of simulated

III. RAILWAY DISTRIBUTION FEEDER

Fig. 4 shows the typical railway distribution feeder and the connection from the solar power plant is shown with DPST. The 132 kV State utility is supplying three phase supply, from which two phases are dropped. In general, same R-Y phases are chosen, but here the author has chosen different phases Y-B and Y-R for load balancing (justification of it is beyond the scope of this paper but can be figured out in the Section 'IV'). Whether the supply utility is fully or partially responsible for owning, installation, operation or maintenance is not of importance in this paper.

As can be seen two phases, R-Y, Y-B, Y-R are dropped along 50 km traction length and each of these two-phases are connected to double pole (D.P) isolator and double-pole circuit breaker (D.P C.B.). The current transformers measure currents for monitoring and the lightening arrestors (L.A.) are installed as per the guidelines. This 132 kV is stepped down to 25 kV transformer and now one phase is grounded and the other phase is connected to the 25 kV feeder using c.b., L.A. and C.T., which carry the power to feeding posts located near the tracks. The bridging interrupter shown is approximately midway between feeding posts, which is the demarcation point of two zones fed from different phases from adjacent substations, which is normally kept open except when an emergency feed is extended. Below, is shown an electric train is shown collecting power through contact with an overhead (OHE) line using pantograph.

IV. PROPOSED CONTROLLER & DISTRIBUTION FEEDER DESIGN

The proposed feeder and controller is installed at 20-100 km away from the pvt. owned and maintained by solar power plant. Proposed feeder is rated at 100%, thus, it can take the entire load of that section of the Govt/DISCOM railway feeder.

consists of six components - Transmission line, kVar Compensator, Mounting Pole, Booster Transformer, Grounding Transformer and Controller As short transmission lines are considered of length of 100 km or less, this same design with same parameters can be used even if the traction substation is located 100 km away from the solar power plant.

A. Transmission line

The mode of transmission is an overhead (OHE) transmission. As per the existing theory, the shunt admittance is mainly capacitive susceptance \((jωC_L)\) as the line conductance is always close to \(≈ 0\) in decimals because of which it is said as negligible and not taken into correction equations for \(≤ 100\) km. But in this study, the line conductance \(≈ 1\) in decimals, has been put in the equations and power degradation got noticed in the power delivery to the railway distribution grid. This additional power degradation has been taken into account while designing kVar compensator (given in the next subsection). Fig. 6

B. Mounting Pole-1

The high level diagram of mounting poles with components are shown in Fig.

C. Mounting Pole-2

Porcelain 25kV Insulator Fig. 8

D. Booster Transformer

To feed 25KV AC power of railway locomotives, this 415V is boosted to step-up transformers with ratio of 60.241 \(≈ 61\). Despite the Y-Y transformation configuration has no phase angle displacement, the Y-Y transformer is not used due to known inherent issues like third-harmonic, voltage drop at unbalance loads, over-excitation of core in fault conditions, series resonance between 3rd harmonic magnetizing reactance and capacitance, \(C_{LG}\), so in
### Table I. Guaranteed Uninterrupted Power Supply

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<tr>
<th>S.No.</th>
<th>$V_{s1}$</th>
<th>$I_{s1}$</th>
<th>$V_{s2}$</th>
<th>$I_{s2}$</th>
<th>$V_{s3}$</th>
<th>$I_{s3}$</th>
<th>$nH/T$</th>
<th>mW</th>
<th>mW</th>
<th>kHz</th>
<th>mW</th>
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</table>

**Fig. 4: Connection to Railway Distribution Feeder**

In the event of L-G fault, the zero sequence current path will be continuous, causing all the harmonics to propagate through the transformer. In the event of L-G fault occurring on the primary, the $V_{LN}$ on unfaulted phases increases to 173% of the normal voltage. Due to these known disadvantages, costlier, $Y - \Delta$ transformer with grounding transformer is proposed.

OFAF (oil forced/air forced) and this transformer is also installed in traction sub-station along side the rail track.

In this design, the State Utility 132 kV transmission at traction substation is dropped to two transformers of 18 MVA at 25 kV, of which only one transformer works at a time in service and the other transformer remains in standby mode as an auxiliary transformer. On a separated single pole:

The voltage at the input and output of the booster transformers are constantly monitored.

Fig. 9
To mitigate the effects of unbalancing from single phase traction load, compensator

The booster transformer is rated at 18 MVA. These transformers are in one way similar to the traction transformers but will be customly designed for traction purpose. The bus bar voltage varies with +10% and -5% i.e. between 27,500 V and 23,750 V, with the nominal supply at 25,000 V. The frequency is between 48.5 Hz and 51.5 Hz with nominal frequency of 50 Hz. The transformer is rated with overload of 50% overload for 15 min and 100% overload for a period of 5 min. The transformer also has off-load changers, which can be operated locally or by remote control with taps from +10% to -15% in steps of 5%. Buchholz relay (a gas detection relay) assembly is installed with transformers as a protective device.

The Vacuum Circuit Breaker (VCB) to be installed instead of SF$_6$, with the capability to handle magnitude of short circuit current in the range of 4 kA

25 kV Single Pole

The Buchholz relay assembly is provided on transformers to detect evolution of gas caused due to internal faults. Analysis of the composition of gas collected will indicate the nature of fault.

Dissolved gas analysis (DGA) provides an important means in the art of condition monitoring of power transformers and other oil-filled equipment. Of the various methods of gas analysis. Gas Chromatography (GC) is one of the most efficient and rapid method, eminently suited for detection of incipient faults and for monitoring of growing faults which are not always revealed by established routine tests etc. in order to timely detect the deterioration of insulation, oil sample shall be drawn annually and subjected to gas chromatography.

E. CB

F. Lightning Arresters

G. Isolator

H. current transformer

I. Battery

110V, 200Ah lead acid cells for control, protection and indication circuits.

110V or 72V, 40Ah lead acid batteries for operation of circuit breakers and interrupters and motor-operated isolators.

J. Grounding Transformer

CONCLUSION

The author has presented solar plant structure, which can be used to supply power in the case of emergency of partial grid failure or otherwise it could motivate investors to design remote solar grids which can be used for rail electrification.

This paper can motivate manufacturers to invest which otherwise could help them to prepare in the event of grid failure or other emergency disaster situations.

The booster transformer can be replaced with tap-changing transformer

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**Abhishek Bansal** The author was born on 6 Feb 1983 in Delhi, India and had been an amateur scholar, fully self taught, had self studied various engineering & mathematical fields/specializations, & medical sciences. He had been working as an independent researcher and as a practicing professional engineer for over 18 years with many industries, with last designation held as Sr. Electronics Design Engineer (Sr. Manager - R&D) in a pvt company. The dataport of the author can be accessed at https://ieee-dataport.org/authors/abhishek-bansal and his ORCID identification number is 0000-0002-2572-9004.