Design of Hybrid Controller for Voltage Profile Enhancement at Battery Energy Storage System Terminal of Solid State Transformer Based Charging of Electric Vehicles

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Abstract-This paper presents a new design for charging an electric vehicle. It incorporates battery energy storage system. There is no need for converters between the electric vehicle and the battery energy storage system. Two battery strings were introduced for reliability's sake and were separately charged by two solid-state transformers. The proposed design has increased the efficiency compared to the conventional Low-frequency transformer based. The paper discusses mathematical modelling of solid-state transformers. The battery energy storage system reduced the peak demand on the grid. Fast electric vehicle charging stations reduce the maximum required grid connection power and avoid the upgrade of grid infrastructure by using the stationary battery energy storage system.The second part of the paper discusses the integration of renewable energy sources and battery energy storage systems to the Direct Current bus through a forward buck converter .They will cause voltage variations, and similarly, changes in load cause terminal voltage variations. So to keepthe voltage constant to 800 volts at terminals that supply power to electric vehicles, a novel design of line booster is implemented in the Forward converter along with controllers. Together they are named hybrid controllers. one is fuzzy control based and the other one is proportional plus integral control based and implemented in Matlab/Simulink to verify its performance. A comparison is made based on the hybrid controller's output voltage, In fact, the fuzzy-based hybrid controller is the better one.It is simple and easy to design, whereas proportional plus integral control needs tuning to get the output voltage .Both the hybrid controllers will control the switching device of the forward buck converter ,thereby controlling the output voltage to 800V.

Keywords Solid state transformer, Battery energy storage system, Electric vehicles ,Fuzzy logic controller, Proportional plus Integral controller,Line booster.

1. Introduction

The number of cars and trucks worldwide has been expected to exceed 2.5 billion by the year 2050.All of these vehicles will use a lot of fuel[1]. Electric vehicle usage in road transport will reduce emissions. The global demand for electric energy is increasing rapidly, as is the expansion of powersystems.This call for demand-side management[2].The number of electric vehicles (EVs) in the world has increased from 3 million in 2017 to over 7.2 million in 2020 and their popularity has been increasing in recent years [3].

Range anxiety implies that the EV owners will lose the EV battery charge over long distances .when an EV is charging they have to wait a long time .The sale of EVs depends on charging speed ,which is a concern for potential EV owners [4].The Tesla Model S and Model X, both of which can recharge at 120 kW, are currently the quickest charging EVs. To address possible EV owner concerns, EV charging power is expected to grow in the future, with 350-400 kW charging stations being suggested. [5-6].As the number of electric vehicles grows, so does the use of fast charging stations, which means increased fast-charging power and potential difficulties for the electrical grid infrastructure. [7]. The local electrical grid infrastructure may not be sufficient to handle the high power grid connection required at the site where the fast-charging station is required.

The long-term answer is to improve the current electricity grid infrastructure to allow for more power at the fast charging station location, but owing to infrastructure and civil works, this is likely to be costly. [8].The new approach, as illustrated in Figure 5, is to employ stationary energy storage at the fast charging station location to buffer the energy between the electrical grid and the EVs charging there.Because the required power capacity from the electrical grid is lower as a result of this approach, an expensive energy grid infrastructure update may not be necessary.

The paper's novelty is in the relationship between the size of stationary energy storage ,solid-state transformers,and no converters between charger and EV which reduces losses and thus increases efficiency.The paper further discusses two strings of battery storage , which increase the reliability and the second part of the paper discusses the integration of renewable energy sources and battery energy storage systems into the direct current bus through a forward converter .They will cause voltage variations , and similarly ,changes in load causes terminal voltage variations.

So, to keep the voltage constant at 800 Volts at terminals that supply power to electric vehicles , a novel design of line booster is implemented in the Forward converter along with controllers, together they are named hybrid controllers .one is fuzzy control based and the other one is Proportional plus Integral control based and implemented in Matlab/Simulink to verify its performance.A comparision is made based on hybrid controllers' output voltage, In fact the fuzzy-based hybrid controller is the better one.It is simple and easy to design whereas proportional plus integral control needs tuning to get the output voltage and does not perform well in non-linearity.Both the hybrid controllers will control the switching device of forward buck converter, thereby output voltage is controlled to 800V.

The paper is structured as follows: Section 2 discusses the solid state transformer review and mathematical modeling; Section 3 discusses the development of the double string battery energy storage system and hybrid renewables integration to DC–bus for electric vehicle charging.;Section 4 discusses the control of the forward buck converter switching device using fuzzy logic and PI controller;Section 5 discusses the line booster development and design of Hybrid Controller-1 (line booster+ Fuzzy control) and Hybrid Controller-2 (line booster+ PIcontroller);Section 6 discusses the simulation results.

2. Solid State Transformer Review

Solid state transformers have rapidly advanced over the last two decades, and they are now being used in traction applications for the replacement of low frequency transformes, which leads to weight and volume reduction ,and significant reliability gains can be achieved.[9].The SST can be used to charge the EV's by replacing the conventional transformer.Figure 1 below shows the solid state transformer's block diagram.

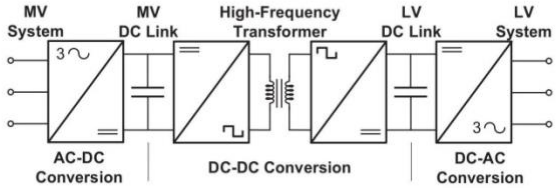


Fig.1. The solid state transformer's block diagram[10]

The SST architecture has provision for supplying power to DC loads . The SST arrangement includes AC-DC,DC-DC and DC-AC stages of conversion an efficiency of .ηSST = η2AC-DC · ηDC-DC =94% is predicted [11].

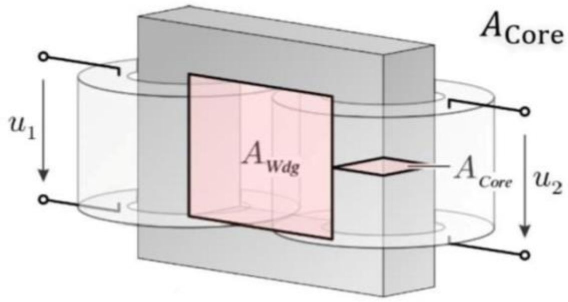


Fig.2. Transformer core [12]

Area Product: $A_{core}.A_{wdg} = \frac{\sqrt{2}}{\pi}\frac{P_t}{K_w J_{rms} B_{max} f}$ (1)

Volume: $V \propto (A_{core}A_{wdg})^{\frac{3}{4}} \propto \frac{1}{(f)^{\frac{3}{4}}}$ (2)

The volume of the core reduces as the frequency rises. Frequency conversion necessitates the use of power electronics. As can be seen from the area product, increasing the operating frequency of a transformer allows for a reduction in volume and weight without increasing the winding current density J_{RMS} and/or the overall core flux density B_{MAXT} (and thus degrading the efficiency).ie

The product of the central cross section area A_{CORE} and the winding window area A_{WDG}, which determines the relationship between the physical size and/or volume of a transformer and the power to be transmitted, as seen in equation-2. where f denotes the transformer operating frequency and k_W denotes the winding window filling factor.[13]. The design equation of the transformers is shown in equation -3.

$$V_{pri} = \sqrt{2}.\pi.f.N_{pri}.\varphi_m = 4.44.f.N_{pri}.B_m.A \quad (3)$$

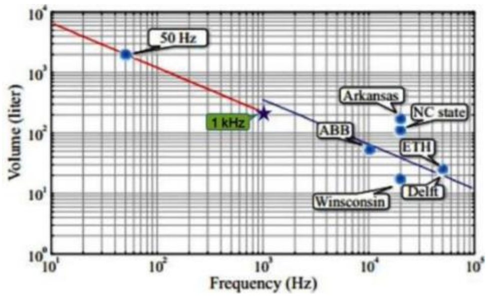
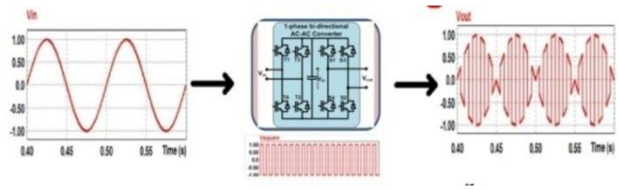


Fig.3. Various transformer designs with various operating frequencies achieve different volumes (all scaled to 1MW power rating)[14].

SSTs are ideally suited to systems with volume and weight constraints, as well as higher power transfer efficiencies. link to MV (as opposed to other discrete power electronic converters that use a low-voltage (LV) input controllability of future differentiation with MF transformers (as opposed to conventional LF transformers). Controllability is a function of an SST, which means it can regulate the input and output voltages and currents (and, in most cases, the output frequency) as well as power flows, and it can shield loads from power system disruptions or the power system from load disturbances. In Figure 3 ,the red line uses the silicon steel core and the blue line uses other core materials like ferrite etc. Using silicon core material we can go to frequencies of 1 to1.5 KHZ.

2.1 Mathematical modelling single phase:(low frequency AC to high frequency AC transformation)



$$V_{in} = \sqrt{2}\,.V_{in_{rms}}.\sin(\omega_s.t)(4)$$

$$\times\, s_{square} = \frac{4}{\pi}\,.\sum_{n=1,3,5\ldots}^{\infty}\frac{1}{n}\cos(n.\omega_{sq}.t) \quad (5)$$

$$V_{out} = V_{in_{rms}}\,.\begin{bmatrix} 0.9.\sin(\{\omega_{sq}\pm\omega_S\}.t) \\ +\,0.23.\sin(\{3\omega_{sq}\pm\omega_S\}.t) \\ +\,0.15.\sin(\{\{5\omega_{sq}\pm\omega_S\}.t) \\ +\,high\ order\ terms \end{bmatrix} \quad (6)$$

The grid sinusoidal voltages is multiplied with medium frequency square wave as shown in equation (4) & (5) and the resultant voltage from equation (6) is fed to the High frequency transformer ,that have sinusoidal envelopes .

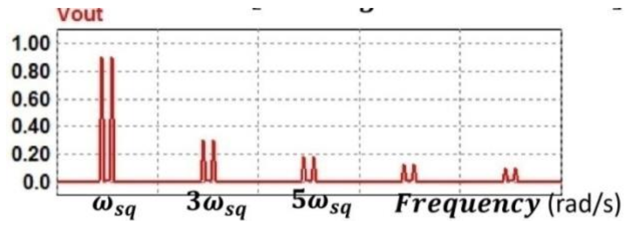


Fig.4. Output voltage vs Frequency[15]

From figure4 and equation-6 observed that the transformer V_{pri} has frequency components only around the square wave Switching frequencies fsq and not at low frequencies this will lead to use of high frequency transformers and system size is reduced .

3. Double String Battery System for Solid State Transformer (SST) Based Electric Vehicle (EV) Charging Station Development.

Previously electric vehicles(EV) are plugged in at the charging port which served as an interface to the Battery energy storage system.String-1 is charging the EV while string-2 recharges through a grid connected solid state transformer DC output voltage. Low frequency transformer which supplies the power in the charging infrastructure substation ,is bulky and does not have any fault handling [16].soild state transfomer can do above defects .It will charge the strings and then the strings supply the DC power to the EVs or else it can directly supply the DC power to the Evs.But proposed design shown in figure 5 supply power to the EVs through strings ,mainly to reduce the waiting times of the EVs as the number is increasing year by year ,and to reduce the burden on the grid and avoid the charging infrastructure upgrade .This also reduces the cost of paying charge to the grid owners because of the storage provided.

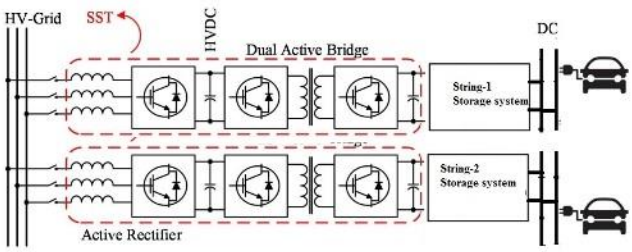


Fig.5. Proposed double string system.[17]

For voltage scaling and galvanic separation, today's power grids depend on passive transformers operating at 50 Hz or 60 Hz. Although these components succeed in terms of performance and dependability, their passive design severely restricts control options. SSTs are power electronic networks that link medium-voltage grids to local low-voltageAC or DC delivery systems or microgrids. SSTs offer voltage leveltranslation and galvanic separation, as well as a high degree of controllability and stability, allowing for additional features such as reactive power compensation, active harmonic filtering, peak load sharing, and so on.Here I considered the performance and power density of the considered bidirectional distribution-level SST systems. Grid voltages of 11 kV and 415 V are considered, with a power spectrum of about 1 MVA. The optimum Si IGBT blocking voltages for the described voltage levels in terms of efficiency and power density have been discovered to be 1200 V or 1700 V. One fully rated 80 kW converter cell has been realized, despite the fact that four cascaded converter cells are needed per phase[18]

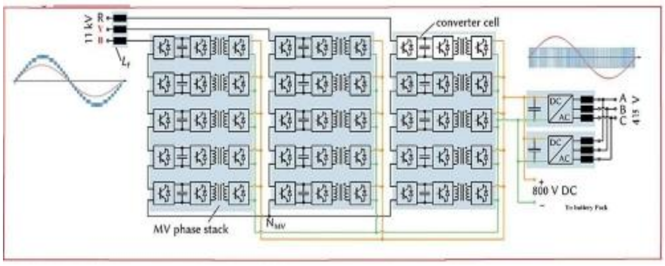


Fig.6. Internal structure.

3.1. Hybrid Renewable energy integration with DC-Bus

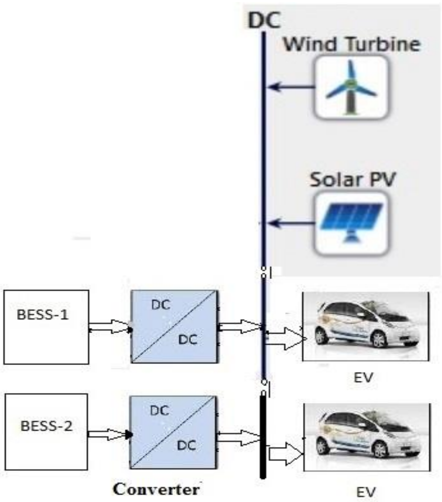


Fig.7. Battery energy storage system with Forward Buck DC-DC converter.[19]

Due to the intermittent nature of renewable energies, HRES is employed for the generation of power, and it also reduces environmental degradation. [20]

In case the power going to Electric vehicle need a constant terminal voltage then fuzzy control based Forward Buck converter is used which will maintain a constant voltage at DC bus irrespective of line and load variations ,and also the solar and wind power integration with DC-bus their output voltage also needs to be maintained constant this methodology can also be applied to them.For analysis purpose, i taken resistive load .But in a particular case the fuzzy did not maintain the constant output voltage .This is tackled by (line booster + fuzzy control) together and is comparedwith (linebooster+PI-controller).All these scenarios are discussed one by one.

4. Control Strategy for Forward DC-DC Converter

5.1. Fuzzy logic controller Design in Forward Buck converter.

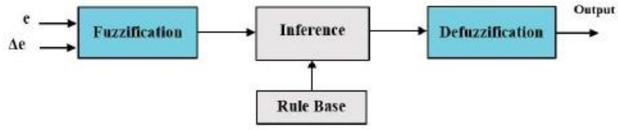


Fig.8. Fuzzy logic stages Block diagram[21]

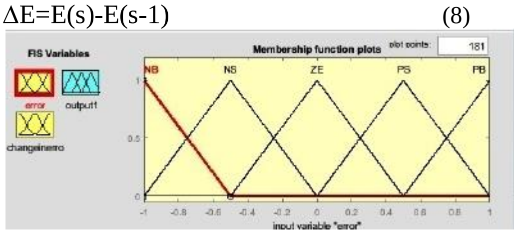
L.A.Zadeh introduced the fuzzy control method.It is fast and less difficulty in implementing .In Figure 8 ,the fuzzy logic controller takes error and change of error as inputs and produces duty cycle as output and is given to the pwm generator which controls the on/off of the mosfet and produces the required output voltage. Fuzzification,fuzzy inference system and defuzzification are the three parameters .Fuzzy variables are represented as fuzzy-sets called membership functions in the range 0-1

Fuzzification:

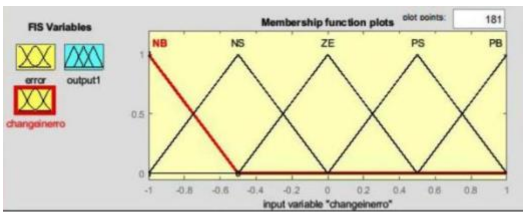
It will convert the crisp value to Fuzzy value .Error E and change of error ΔE are the two inputs .See the equations 7&8

$$E = V_{out} - V_{ref} \quad (7)$$

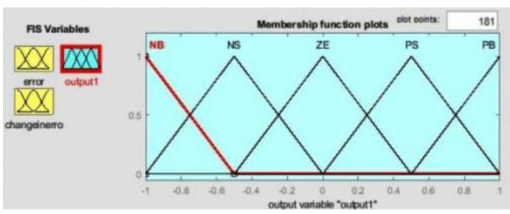
$$\Delta E = E(s) - E(s-1) \quad (8)$$



(a)



(b)



(c)

Fig.9. (a) Membership function Error (b) Membership function change in error (c) Membership function output

Figure 9(a),(b),(c) shows 5 linguistic variables are assigned to input and output variables which generates optimal duty cycle value for controlling the mosfet switch and thereby the output voltage.

Table 1. Fuzzy if-then rules

Error/Change of Error	NB	NS	ZE	PS	PB
NB	PB	PB	PB	PS	PS
NS	PB	PS	PS	PS	ZE
ZE	PS	PS	ZE	NS	NS
PS	ZE	NS	NS	NS	NB
PB	NS	NB	NB	NB	NB

Fuzzy Inference engine(Fuzzy rule base): 25 rules has been created and presented in Table 1.The mamdani max-min method is used to make a decision.

Defuzzification:

It uses centroid method and gets the physical value from linguistic value and send the optimal duty value to the switch of

4.2 Proportional plus Integral controller (PI)

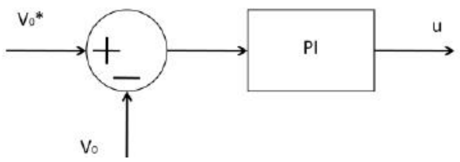


Fig .10. PI-controller Block diagram[22]

The output voltage of the forward buck converter is sensed and compared with the reference output voltage .The error obtained is fed to PI-controller.It generates a control signal and ,when compared with the triangular signal, produces for the switch the switching pulse.

$$u(t) = Kpe(t) + Ki \int e(t)dt \quad (9)$$

Where Kp denotes proportional gain and Ki –integral gain.The controller is tuned optimally by using a trail and error method and the values are Kp=10 and Ki=100.

4.3.Specifications of Forward DC-DC Buck converter

Table 2. Ratings of elements used in simulation

Input voltage	800V
Outputvoltage	800V(reference)
Inductor	250mH
Capacitor	100µF
Kp	10
KI	100

5. Hybrid Controllers Design

5.1. Hybridcontroller-1(Line Booster +Fuzzy controller)

The fuzzy logic controller used did not regulate the input voltage when it is less than the reference voltage 800V dc .So this research gap is solved by development of Line booster controller. Refer table 3 for the parameters of line booster.

5.1.1 *Design of Line booster*

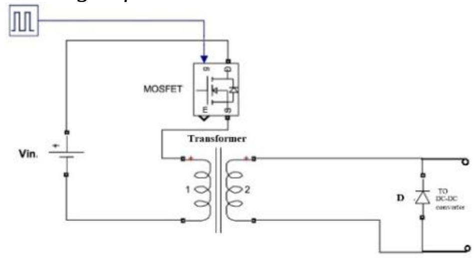


Fig.11. Line booster to inject voltage

Table 3. Parameters for Line booster

Parameters	Values
Vin	100V
Vout	60V
D	60%
Fsw	5KHZ
Linear transformer	100/60V

The figure11 show line booster design which can inject voltage of around 60V which will add to output voltage.A linear transformer with a mosfet switch having fact acting pulses induces an emf in secoundary.It induces approximately

60v .It is added to the ouput voltage .The equations 10&11 represent mathematically above concept.

$$Vout(new)=Vout(old)+Vinject \quad (10)$$
$$Vout=740+60=800V. \quad (11)$$

5.1.2. Block diagram of Proposed Hybrid controller-1 with Forward Buck converter

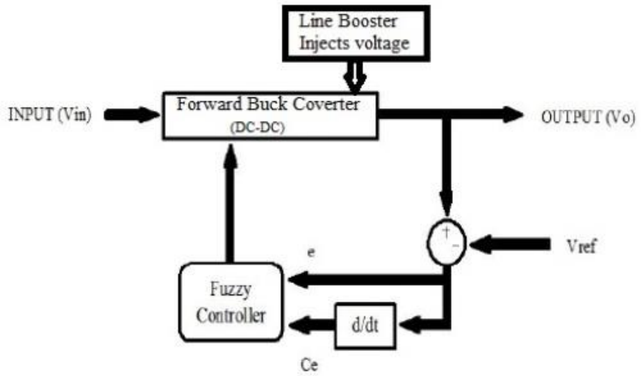


Fig.12. Forward Buck converter(DC-DC) with Hybrid controller-1[23]

The figure 12 shows the block diagram, the novelty is the introduction of line booster to the converter

5.1.3 Flow chart of Hybrid controller-1 (line booster+fuzzy controller)

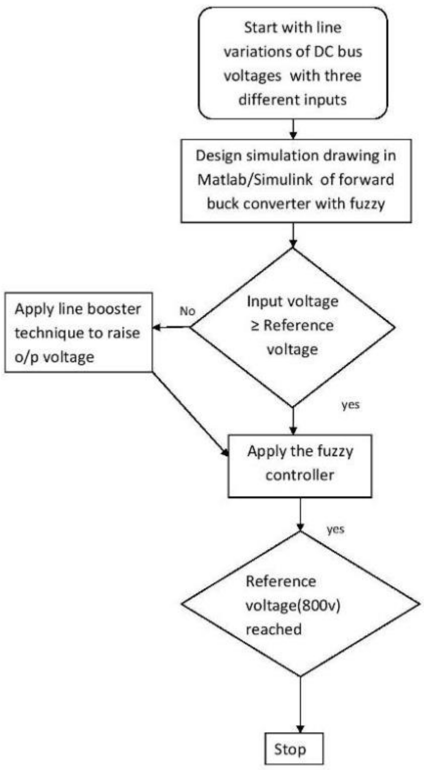


Fig.13. Flowchart of Hybrid controller-1

5.2. Hybrid controller-2(Line Booster +PI controller)

5.2.1 Block diagram of Proposed Hybrid controller-2 with Forward Buck converter.

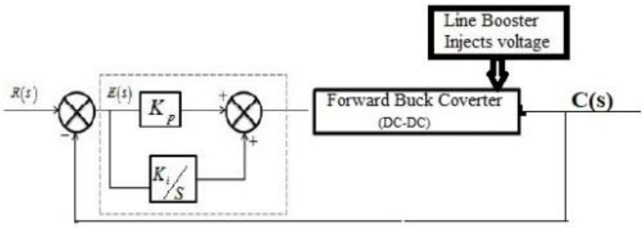


Fig.14. Forward Buck converter(DC-DC) with Hybrid controller-2[23]

5.2.2 Flow chart of Hybrid controller-2 (line booster+PI controller)

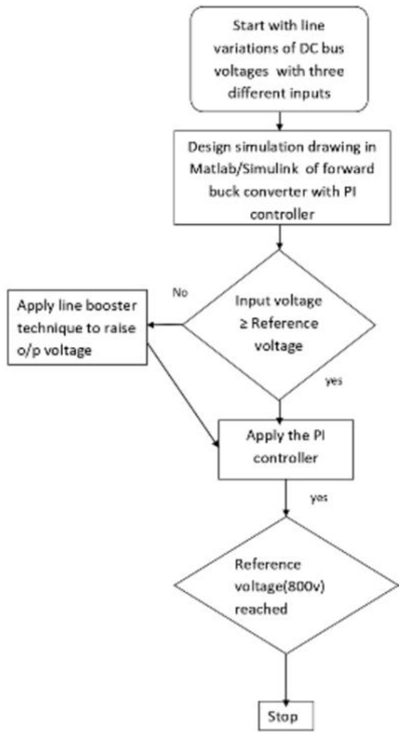


Fig.15. Flowchart of Hybrid controller-2

6. Simulation and Analysis

6.1 Proposed double string system results

The proposed system 11KV /1MW/800V was modelled in MATLAB/Simulink [24] as shown in Figure 6.The output voltage 800V DC of the solid state transformer is charging the Battery energy storage systems (string 1and string -2).Now they are ready for charging electric vehicles. The Electric vehicles (EV) can be flipped such that which string is having energy is engaged This increases the reliability and efficiency as there are no converters between the Electric vehicle(EV) and battery storageenergy systems(BESS).The output voltage waveform is shown in figure 16.

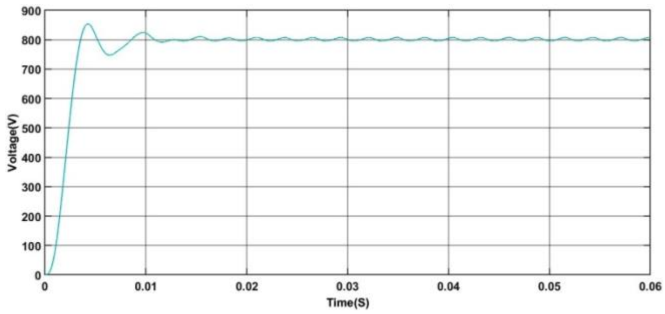


Fig.16. Output voltage vs time

6.2 DC/DC Forward buck converter without controller results.

Initially the forward converter is modelled in matlab/simulink as shown in Figure 17 and line variation effect is observed .For analysis purpose resistive load is taken (RL=20ohm).

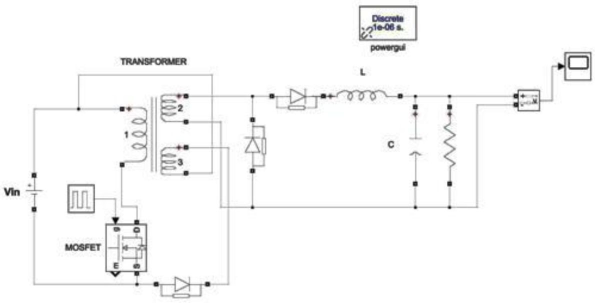


Fig.17. Forward Buck converter with out controller.

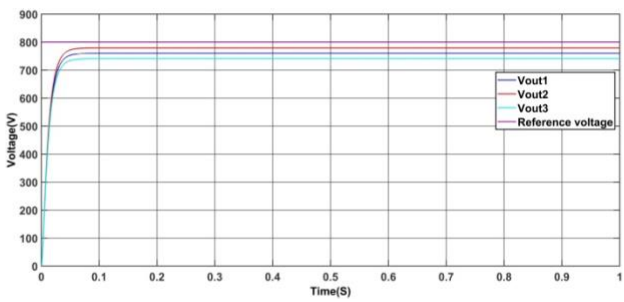


Fig.18. Forward Buck converter output voltage for input Line variations

In this case the input line side voltage variations are coming but the forward buck converter give output voltage other than the reference voltage as per the Table 4and Figure 18 shown ,to regulate to 800V we have to go for fuzzy logic controller.

Table 4. Output voltage for input line variations

S.No	Input voltage	Outputvoltage (withoutcontroller)	Reference voltage(desired)
1	800V	760V	800V
2	820V	780V	800V
3	780	740V	800V

6.3. DC/DC forward buck converter with Fuzzy logic controller results

Initially the forward buck converter with Fuzzy controller is modelled in Matlab/Simulink as shown in Figure 19 and line variation effect is observed

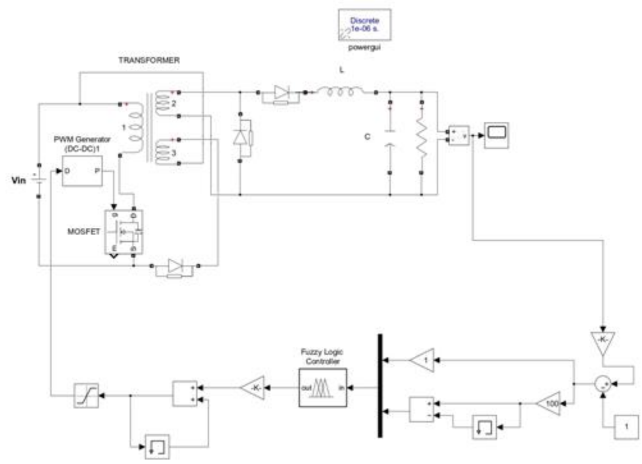


Fig.19. Forward Buck converter with Fuzzy Controller

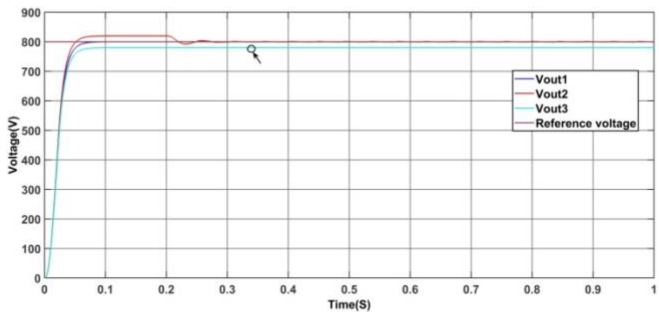


Fig.20. Fuzzy controlled output voltage for Line variations

Here if we look at the table 5 and figure20 (Vout3),for first two observations the fuzzy controller maintained the reference voltage .In the third observation it doesn't maintain the reference voltage since the input voltage is less than the reference voltage .Hence the fuzzy controller failed .The research gap can be corrected by using my hybrid controller(Fuzzy +Line booster)

Table 5. Fuzzy controlled output voltage for input line side variations

S.No	Input voltage	Fuzzy control output Voltage	Reference voltage (desired)
1	800V	800V	800V
2	820V	800V	800V
3	780V	**780V**	800V

6.4. DC/DC forward buck converter with hybrid controller -1(line Booster+Fuzzy controller) results.

The line Booster will inject 60V to circuit that will add to output voltage and Now from this point onwards fuzzy logic will regulate the output voltage to 800V.

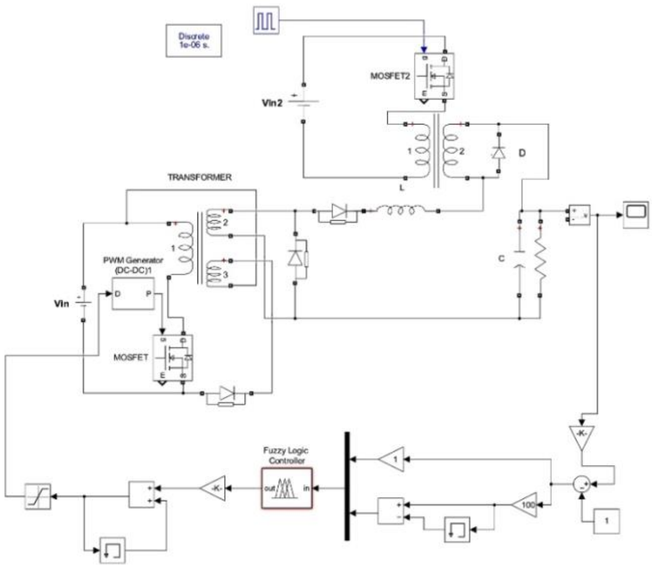
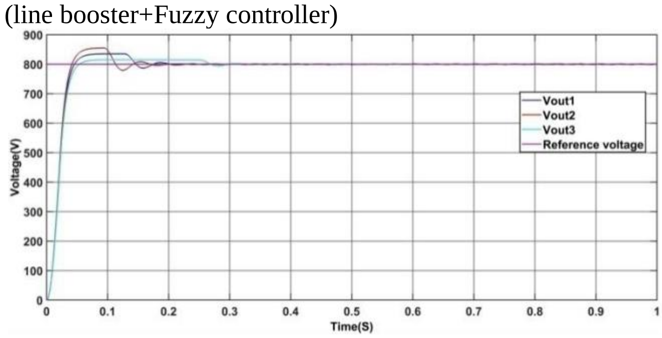
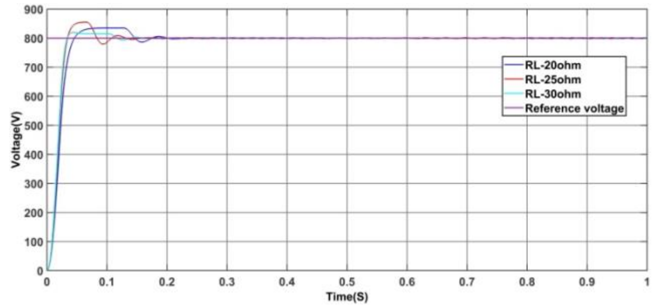


Fig.21. Forward Buck converter with Hybrid controller-1 (line booster+Fuzzy controller)



(a)



(b)

Fig.22. (a) Hybrid controller-1 output voltage for Line side Variations

(b) Hybrid controller-1 output voltage for Load side Variations

From Figure 22(a) In all three cases (Vin=800V,820V&780V) this hybrid controller-1 maintained constant voltage 800V. From Figure 22(b) it is very clear that for different load resistance values (RL-20ohm,25ohm & 30ohm) the hybrid controller-1 maintained the constant voltage 800V.

6.5.DC/DC forward buck converter with hybrid controller-2 (line booster+ PI-controller) results.

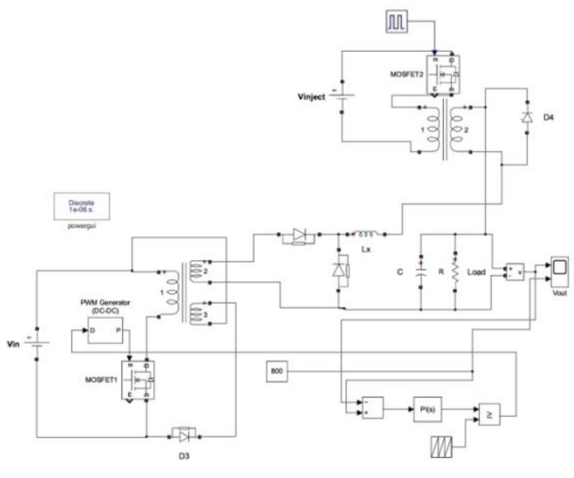
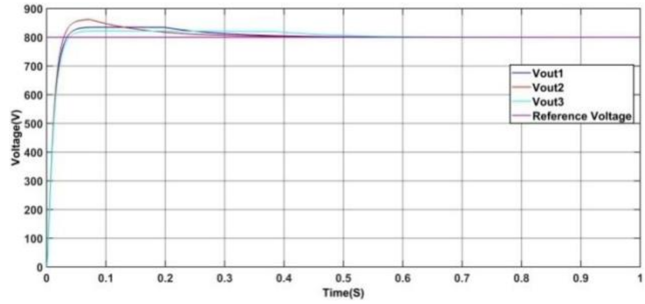
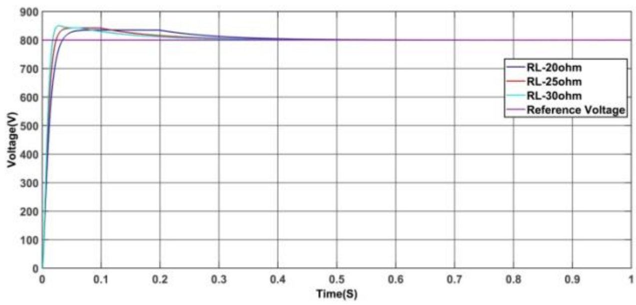


Fig.23. Forward Buck converter with Hybrid controller- 2 (Line booster+PI-controller).



(a)



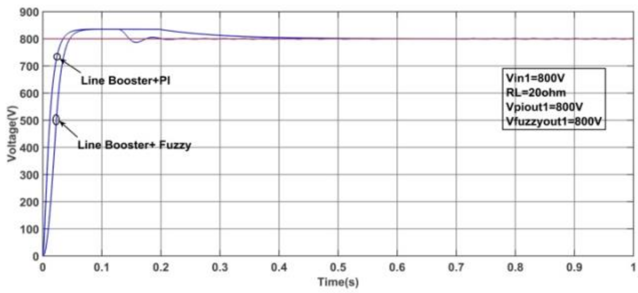
(b)

Fig.24. (a) Hybrid controller-2 output voltage for Line side variations
(b) Hybrid controller-2 output voltage for load side variations

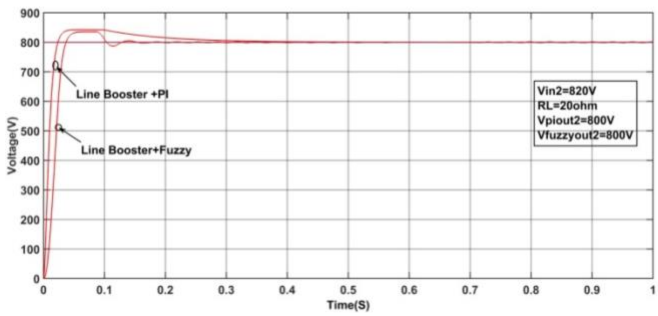
From figure 24 (a) it is very clear that the hybrid controller-2 maintained the constant output voltage to 800V for all the three cases of input values((Vin=800V,820V&780V). .From figure 24(b) it is very clear that the hybrid controller-2 maintained the constant output voltage 800V for different load resistancevalues . (R_L-20ohm,25ohm & 30ohm)

6.6. comparision of hybrid controller-1 and hybrid controller-2 output voltages

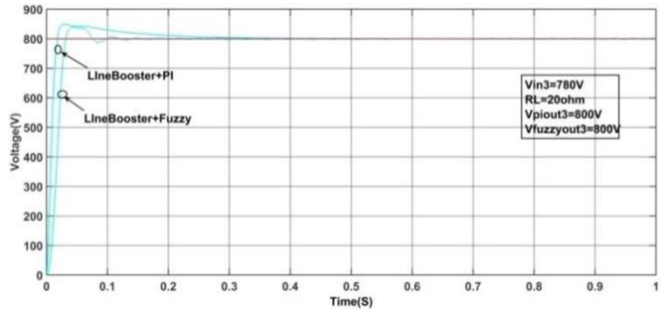
6.6.1 comparision of Results for input line variations.



(a)



(b)



(c)

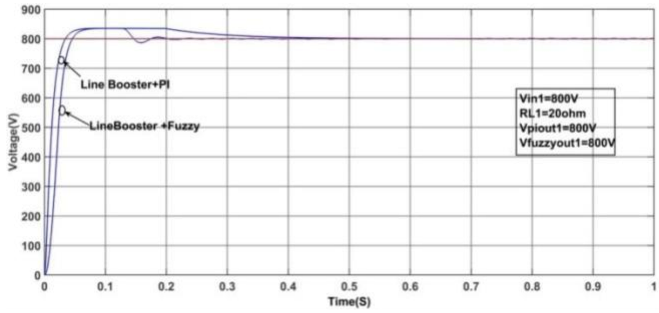
Fig.25.(a) Hybrid controller-1 & 2 comparision for V_{in1}=800V &R_L =20Ω
(b) Hybrid controller-1 & 2 comparision for V_{in2}=820V & R_L=20Ω
(c) Hybrid controller-1 & 2 comparision for V_{in3}=820V & R_L=20Ω.

The results of hybrid controller 1&2 compared, for input line variations .The line can be varying as 800V,820V and 780V as shown in Fig25(a) ,Fig25(b) & Fig25(c) respectively.The Mathematical representation is shown in Table 6.

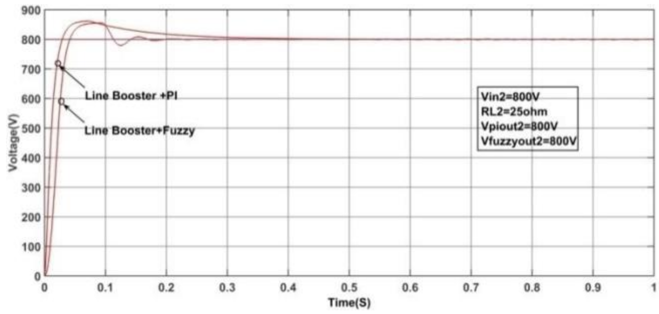
Table 6. Mathematical Results , comparision of Hybrid controllers 1 & 2 for Line voltage(DC) variations.

Vin1=800V-DC					
Hybrid Controller -1&2	*V_{in1}*	*V_{out1}(regulated)*	*Rise time*	*Overshoot*	*Settling Time*
Line booster+ PI]	800V	800V	19.717 ms	4.733%	285.101 ms
Line booster+ Fuzzy]	800V	800V	25.264 ms	4.737%	121.180 ms
Vin2=820V-DC					
Hybrid Controller -1& 2	*V_{in2}*	*V_{out2}(regulated)*	*Rise time*	*Overshoot*	*Settling Time*
Line booster+ PI]	820V	800V	17.978 ms	8.152%	221.281 ms
Line booster+ Fuzzy]	820V	800V	24.122 ms	6.986%	111.050 ms
Vin3=780V-DC					
Hybrid Controller -1& 2	*V_{in3}*	*V_{out3}(regulated)*	*Rise time*	*Overshoot*	*Settling Time*
Line booster+ PI]	780V	800V	21.045 ms	2.577%	388.179 ms
Line booster+ Fuzzy]	780V	800V	27.282 ms	1.531%	27.334 ms

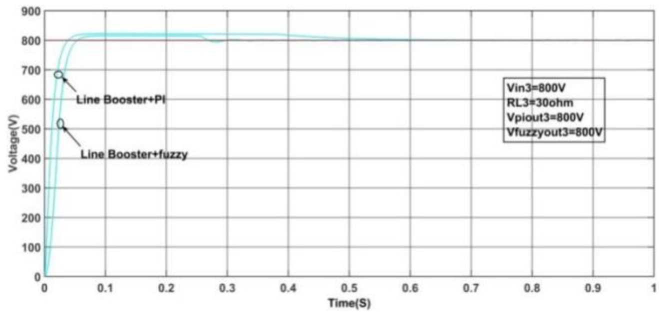
6.6.2 .comparision of results for Load variations .



(a)



(b)



(c)

Fig.26.(a) Hybridcontroller-1&2 comparision for V_{in1}=800V &R_{L1} =20Ω

(b) Hybridcontroller-1&2comparision for V_{in2}=800V & R_{L2}=25Ω

(c) Hybridcontroller-1&2comparisionfor V_{in3}=800V & R_{L3}=30Ω.

The results of hybrid controller 1&2 compared, for load variations .The load can be varying as 20Ω,25Ω&30Ω. as shown in Fig26(a) ,Fig26(b) & Fig26(c) respectively.The Mathematical representation is shown in Table 7.

Table 7. Mathematical Results ,comparision of Hybrid controllers 1 &2 fo r Load variations.

R_{L1}=20ohm					
Hybrid Controller -1&2	*Vin1*	*Vout1 (regulated)*	*Rise time*	*Overshoot*	*Settling time*
[Line booster + PI]	800V	800V	19.717 ms	4.733%	285.101 ms
Line booster+ Fuzzy]	800V	800V	25.264 ms	4.737%	121.180 ms
R_{L2}=25ohm					
Hybrid Controller -1&2	*Vin2*	*Vout2 (regulated)*	*Rise time*	*Overshoot*	*Settling time*
[Line booster + PI]	800V	800V	14.247 ms	5.851%	217.412 ms
Line booster+ Fuzzy]	800V	800V	20.450 ms	6.986%	80.264 ms
R_{L3}=30ohm					
Hybrid Controller -1&2	*Vin3*	*Vout3 (regulated)*	*Rise time*	*Overshoot*	*Settling time*
[Line booster + PI]	800V	800V	11.615 ms	5.851%	136.276 ms
[Line booster +Fuzzy]	800V	800V	19.680 ms	2.577%	85.656 ms

From above tables 6 & 7 ,the rise time, over shoot and settling time parameters for input line variations and load variations also ,for both hybrid controller-1(line Booster +fuzzy) & Hybrid controller-2(Line Booster +PI) output voltages of forward buck converter is noticed and certainly increased the power quality.

7. Conclusions

This paper initially proposed a Solid state transformer-based charging station for Electric vehicles ,that employs a battery energy storage system.Simulation results of 11KV/1MW/800V Solid state transformer are carried out and connected to Battery energy storage system namely string-1 and string-2 for charging the Electric vehicles. Battery energy storage system completely decouples the grid and reduced the demand on grid and Low frequency transformer is replaced by Solid state Transformer.

Secondly the Forward Buck converter terminals voltage is regulated for input line variations and load variations using hybrid controllers 1&2.Line booster novel design is implemented with fuzzy controller and Proportional plus integral controller separately.Simulation results were compared ,overshoot and settling time is less for Hybrid controller-1(linebooster+Fuzzy) when compared with Hybrid controller-2(line booster+PI).

The hybrid controller proposed will regulate line and load variations both .But existing techniques will regulate load variations only when compared .

The Proportional plus integral controller needs tuning and it is complicated .The parameters are to be adjusted every time to get satisfactory results.But Hybrid controller 1(Line booster+fuzzy), is the simplest method and its performance is good when compared with hybrid controller-2 which uses PI controller.

The proposed techniques can be applied to wireless charging of Electric vehicles and experimental verification of the simulation results are the future scope of this research work.

Appendix: A_{core}: core cross section area; $A_{wdg::}$ winding window area; B_{max}: Maximum core flux density ; J_{rms} winding current density; f: frequency ; K_w winding window filling factor; V:voltage ; P:power; π pi 3.14; $K_{i\,:}$ integral gain; K_P: proportional gain : E error; ΔE :change in error; $V_{out:}$output voltage; V_{inject}:injected voltage.

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