DESIGN & SIMULATION OF WIND TURBINE GENERATOR–BATTERY ENERGY STORAGE UTILITY INTERFACE CONVERTER TOPOLOGY

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ABSTRACT

A medium-voltage (MV) wind turbine generator (WTG)–battery energy storage (BESS) grid interface converter topology with medium-frequency (MF) transformer isolation is proposed in the paper. This system makes a three-port network with various series connected ac–ac converters. This changes the low-frequency (50/60 Hz) utility MV to MF (0.4 to 2 kHz) ac voltage. It is done by modulating it with MF square wave. This voltage is then given to the primary windings of MF transformer. The WTG side and the BESS side are connected to the secondary and tertiary windings respectively, after power conversion. The generated power in the WTG is fed to the secondary windings of MF transformer through a three-phase PWM rectifier and a three-phase pulse width modulation (PWM) inverter. The three-phase PWM inverter transfers power between the BESS and the tertiary winding. PI and DQ control strategies are used to control the utility grid sinusoidal currents, the WTG output, and the battery current. The control can manage voltage swells/sags and provide low voltage ride-through capacity

Keywords: Battery Energy Storage (BESS), Low Voltage Ride through (LVRT), Medium-Frequency (MF) Transformer, Three-Port Network, Wind Turbine Grid Integration.

I INTRODUCTION

Renewable form of energy sources like wind, solar, etc., produce variations in electric power. Interlinking these sources to the utility grid at high rate may affect the frequency and voltage regulation. These natures may put the stability of the grid to danger, leading to serious power quality issues. Introducing energy storage technologies to support the power produced from photovoltaic panels, wind turbine generators, etc., helps to eliminate the challenges like capacity firming, smoothing, time-shifting etc. This is how an energy storage system is important to maintain the active power in a renewable energy grid. The storage source used in the WTGs can be flywheels, batteries, electric double layer capacitors, etc. The batteries and electric double layer capacitors (EDLC) have been of big part in the power electronics industry. But their interface to the utility grid is more challenging, like in the medium voltage scale [1][4].

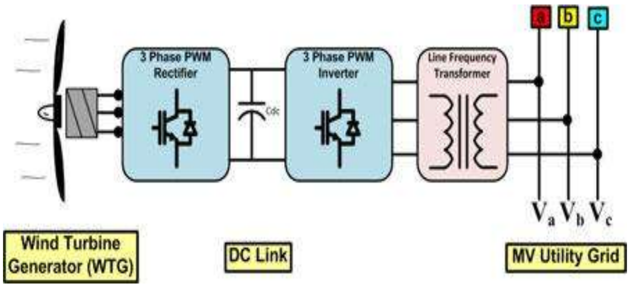


Fig. 1. Conventional WTG power converter topology.

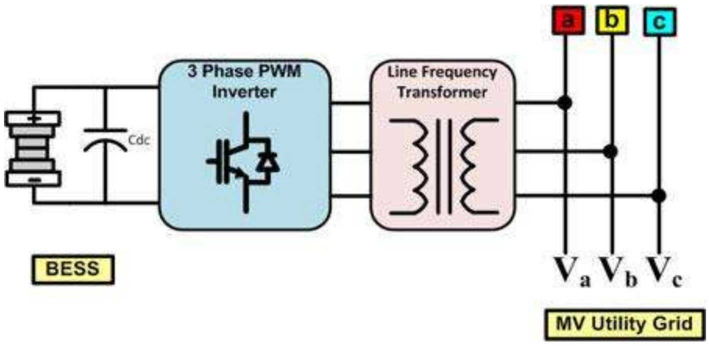


Fig. 2. MV utility–energy storage interface topology with line frequency trans-former and PWM rectifier

Wind turbine generator is able to operate at extreme power coefficient over a vast range of wind speeds [4]. Permanent magnet wind turbine generators are becoming more useful for energy conversion in high power mostly due to high power flexibility and density during working. The power converter has to be made to withstand the whole of the generated power, much of the research focus has been to attain higher efficiencies at smaller footprint. A famous power conversion method used for Permanent magnet wind turbine generator is the direct drive topology (see Fig. 1).

Different methods have been introduced in the literature to connect battery energy storage systems with the utility [5]. The usual method gives a line frequency transformer to charge and discharge a low voltage battery bank [5] (see Fig. 2). This method also needs a line frequency step-up transformer to be connected to a medium-voltage grid. A 5-MVA, 2.5-MW·h Battery energy storage is used in [6] with lead acid batteries. It is based on parallel operation of 12-pulse converters to achieve the expected power rating. The presence of separate big line frequency transformers is needed to connect the wind turbine generators and battery energy storage elements to the medium voltage utility grid are its general drawback with these topologies. Pulse width modulation rectifier followed by a high-frequency-link dc–dc converter is connected to a battery bank [7] is it's another usual approach. Such connections still needs a step-up line frequency transformer for integration of medium voltage grid.

If we use high-frequency transformer, it will improve the power density, but the cost of transformer core material is high. Insulation failure in the transformer may occur if the high switching frequency at high voltage is done. Lot other such SST structures with different qualities have been introduced for various uses, that can also be applied in wind turbine generators or Battery energy storage connection. All the above structures are dc link oriented and it needs electrolytic capacitors for conversion of power. Lot of structures to connect wind turbine generators systems with Battery energy storage have also been introduced. Many of them introduce different ways of the Battery energy storage integration to the wind turbine generators system dc link. There are some other methods of connecting the two systems at the grid by separate line frequency transformers. The first system is best for power interface of lower ratings, but interconnecting the two systems at the dc link at high power rating needs the transformers. Two different big line frequency transformers needs for the second method.

Three-port system using dual or triple active bridges to interconnect renewable energy system are proposed in and. An identical three-port system is used for wind turbine generators – Battery energy storage medium voltage grid integration. It's wise to use medium-frequency (MF) transformers to get a good balance among the cost, power density, frequency, efficiency, etc., instead of high-frequency transformers or line frequency for high-power wind turbine generators – Battery energy storage. If there is a pulsating dc link, dc electrolytic capacitors can be avoided and this will help to get low losses in switching. These peculiarities can be used to derive needed power conversion.

This paper put forward a new MV wind turbine generators – Battery energy storage grid interconnected converter system with Medium frequency-link with isolation by transformer. The system have a transformer of medium-frequency, it have three sets of windings makes a three-port network with ac–ac converters connected in series on the MV utility part. It has a three phase PWM inverter, and rectifier connected on the WTG side, and the Battery energy storage side is connected with a three-phase PWM inverter. Connection between the WTG with BESS gives a channel to redirect the energy flowing from WTG to the utility grid toward the BESS at the time of low voltage ride through (LVRT). The battery current, the utility grid sinusoidal currents, and the WTG input currents are of excellent quality; but the transformer voltages are of MF at the time. Complete topology of the system shown in Fig. 3. There are some advantages for the system, they are as follows.

1) By using MF-link transformer we can reduced size/weight, it also gives galvanic isolation and required voltage matching between the utility, the WTG, and the BESS.
2) Both WTG and BESS can be interfaced by using single transformer. There is no need of external inductor, the leakage inductances of the Medium Frequency transformer can be used as power transfer reactors.
3) The system got a series connected input-side ac–ac converters, it gives lower voltage IGBTs/MOSFETs and transformer coupling and input capacitors helps for voltage sharing.
4) The power factor of utility and WTG made near unity by modulation of ac–ac converters and PWM rectifiers, and have a current of small low order harmonics.
5) The switching losses are low because of the presence of ac–ac converters and are switched at MF.
6) The system is able to withstand voltage sags and swells, there is no need of change in strategy or topology.
7) Silicon steel or amorphous core trans-formers can be used at magnetic flux density of lower rating because the operating frequency is not very high.
8) The proposed system have high switching frequency operation on the PWM rectifiers due to its flexible, and the transformer core is operated at stable Medium Frequency over whole operating range.

9) With small change in topology LVRT is applied in the system.

In Section II explains the proposed converter topology, equations, operation, and Control strategies. The LVRT feature explains in the Section III. The simulation and experimental results described in the Sections IV and V respectively.

II PROPOSED WTG–BESS UTILITY INTERFACE CONVERTER IN THREE-PORT CONFIGURATION

The structure of the whole system in Fig. 3 can be classified into the following five sections: 1) WTG and BESS; 2) three-phase PWM rectifier and inverter; 3) multilevel ac–ac converter; 4) MF transformer; and 5) control strategy. The experimental results has been briefed to the one-phase circuit as shown in Fig. 4 along with the MF transformer

2.1 Multilevel AC–AC Converter

The each phase of ac–ac converter is composed of multiple levels of one-phase ac–ac H-bridges .The bidirectional switches are composed IGBTs (see Fig. 3). Consider that the IGBTs are rated at 1700 V. Input voltage in rms value for each level of ac–ac converter is 1100 VLL. To interconnect 4160 VLL, we need minimum four ac–ac full bridges connected to each phase in series. The ac–ac converter is modulated at each level with a Medium Frequency ($f_{sq} = \omega_{sq} /2\pi$) square wave. The utility at voltage phase A is V_a , the ac–ac converter switching function Sacac. The primary voltage at transformer of phase A Vpri A can be given by, The line frequency component is missing from the transformer; it can be noticed from the previous equations. The main frequency components shown are the MF ($f_{sq} \pm f_s$).It is important to note that fsq is controlled by the transformer core material. In this condition it is good to construct the core with silicon steel. The silicon steel is of lower cost, and its fsq is taken to be 600.

$$V_a = \sqrt{2} \cdot V_{a,rms} \cdot \sin(\omega_s \cdot t) \quad (1)$$

2.2 WTG and BESS

An 1100 VLL, 2 MW, 20 Hzmax PM WTG is considered for the simulation purposes. The WTG is connected with a 900 Vdc,max , 1 MW/3MW·h lithium ion-based BESS. When the demand is high or low wind, the BESS will give the power to the grid. But when the high wind or low demand, the BESS will get charged.

The WTG is maintained in the simulation by torque adjustments and DQ control on the PWM. A Battery type used in high-power energy storage is Li-ion. Li-ion battery is very effective for high-power energy storage, due to high efficiency, fluctuation in voltage is low, and energy density is high [5]–[7]. It is better to have the battery bank voltage within 1000 V(dc). It's good to have less series connected cells and more parallel connected cells. This will help the battery bank charge balancing and this will provide good power density to the system.

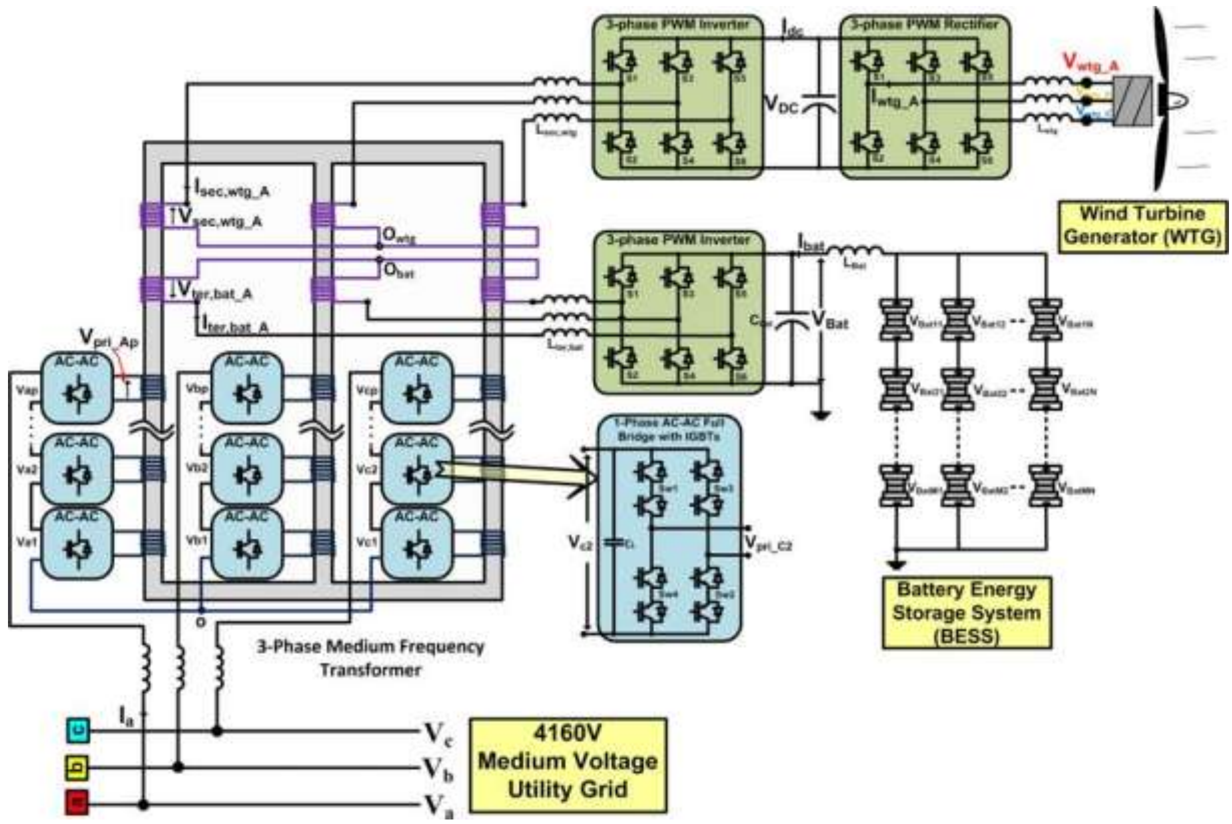


Fig. 3. Proposed WTG–battery energy storage converter three-port configuration with MF transformer isolation for utility grid integration

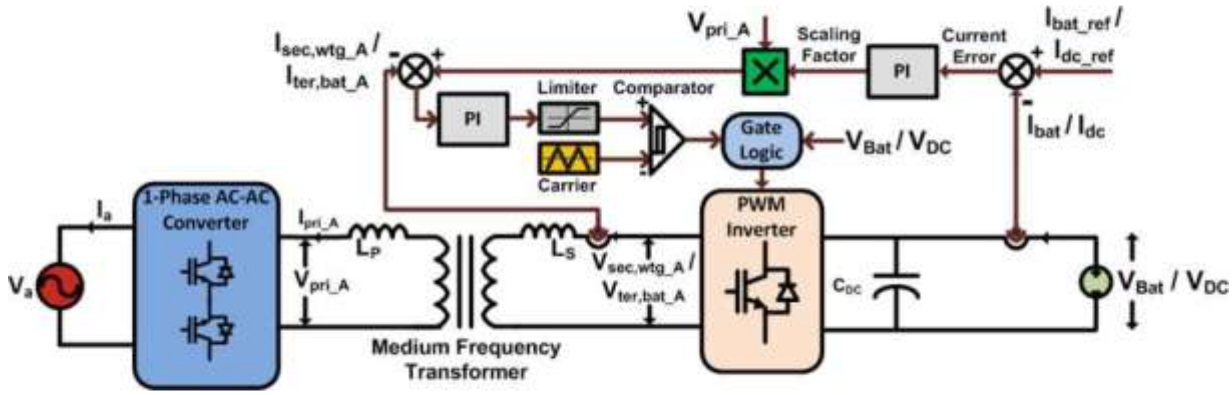


Fig. 4. Per-phase control strategy at the MF transformer of the proposed topology (see Fig. 3) for demand-based power flow regulation among the utility grid, WTG, and BESS (strategy is similar for WTG as well as BESS side).

$S_{acac} = 4/\Pi \sum 1/n \sin(n.w_{sq}.t)$
(2)

$V_{pri\_A} = V_{a,rms} \cdot [\ 0.9 \sin((\omega_{sq} + \omega_s).t) + 0.23 \sin((3\omega_{sq}+\omega_s).t) + 0.15 \sin((5\omega_{sq}+\omega_s).t)$ +high order terms] (3)

The proposed system recommends the maximum voltage of the battery bank to be 900 Vdc at the full charge and 450 Vdc at discharged condition during peak load. When energy demand is low the battery bank gets charged and when there is high energy demand it gets discharged. The battery current ripple has to be maintained within certain limits because the internal heating in the batteries increases with the increases ripple, so it needs additional cooling infrastructure. The battery current ripple does not make Ibat value become negative during charging or become positive at discharging [5], [6].

2.3 Three- Phase PWM Rectifier and Inverter

Single-level per-phase equivalent diagram of the proposed system is shown in fig.4. Vpri_A is The voltage applied to the primary of the transformer, Vsec,wtg_A is the induces voltages on the transformer secondary, and Vter,bat_A the voltage at the transformer tertiary and is based on the turns-ratio. The conventional DQ control is used to govern PWM rectifier at the WTG side, and is used to transmit available wind power to the dc link. The voltage VDC at the dc-link is maintained at 1500V, and this is appropriate for the PWM operation as inverter. The secondary and tertiary windings have similar control and operation of PWM inverters. The inverters have to produce all the main frequency components in Vpri_A for the transformer bidirectional active power transfer (see Fig. 3). The switching function of the PWM inverters is the product of a MF square wave and a line frequency sine wave, and the amount of power to be transferred affects the phase-shifting. This can be obtained by hysteresis control or PI of transformer phase currents

In the Fig. 3, there is only one set of trans-former tertiary windings, but it has a three-phase PWM inverter connected to the BESS. This modular system is able to be expanded in power rating point of view by applying more tertiary windings with some battery banks and PWM inverters. The transformer leakage inductance performs as the power transferring reactors. The rating For a dc link on the WTG side is 1500 V, 2 MW, the IGBTs must be rated at 3 kV, 1000 Apk . The BESS voltage at the peak is Considered as 900 Vdc , 1700 V IGBTs can be used to obtain almost 1000 Apk current rating for a system power of 1 MW.

2.4 MF Transformer

A Medium Frequency transformer is a crucial component of the topology. A high-frequency trans-former have hysteresis losses and a line frequency transformer is bulky so it's better to use a MF transformer. The Medium Frequency transformer have silicon steel core so the hysteresis losses are not high as the line frequency is low. But if we tried to reduce the size by increasing the frequency it will causes the increase in the hysteresis losses also. Above specific frequencies, it is essential to use Nano crystalline or ferrite core, this will brings up the cost of the core of the transformer and insulation requirement also increases to reduce corona effect.

The MF transformer is meant for a 600 Hz core frequency with maximum 0.6 T magnetic field intensity .this arrangements is for rated power low audible noise and low core losses. Amorphous silicon core can be implemented to reduce the core loss more. Lower magnetic field intensity can be used to reduce core saturation effects at MF. The minimum number of transformer turns ratio needed can be calculated based on the PWM rectifier operations and ac–ac converter.

2.5 Control Strategy

The elaborated control technique used for the proposed system is shown in Fig. 4. The figure shows the power flow from the WTG to the utility grid and charging and discharging of BESS. 1) The internal loop regulating the transformer secondary/tertiary currents, Isec, wtg A and Iter, bat A; and 2) the external loop regulating the dc current, Ibat or Idc, are the two major current loops of the control. For the transformer secondary and tertiary currents in the phase, there will be two more internal loops. The outer loop is generally slower compared to the inner loops and is common for all the inner.

The input capacitors and the multiple windings in the transformer will make sure the voltage to be distributed equally in the windings on the utility side. The square wave is used to modulate the ac–ac converter; a “multiple-frequency” voltage waveform is seen in the windings of the transformer. The controller find out the grid demand to measure how much amount of current must flow at any time. The BESS dc current is controlled using this information by switching the PWM inverter on that side. The WTG is controlled to get the maximum power out of it. The battery current reference is maintained to absorb or supply power. The WTG-side PWM rectifier, the dc-link voltage is regulated by the DQ control.

The PWM inverter at the WTG side works like PWM inverter on the BESS side. The hysteresis controller can take position of the inner PI controller. The hysteresis controller which will also do same function as PI controller. There is only a single common outer loop and scaling factor, the phase currents of the transformer will be avoided. The control will assure that the power is equally distributed across the phases.

The power flow mechanism is a current control process, in the transformer both sides of the $B-H$ curve are used and thus we get the reduced core saturation. There will be some harmonics in the system due to transformer current transients; these harmonics can be eliminated using an LC filter.

III. LVRT

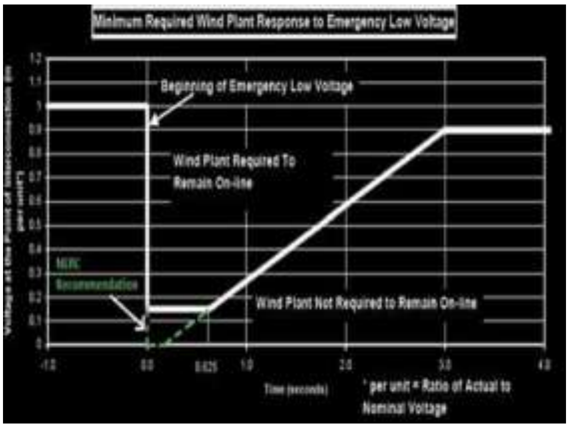
When the grid voltage is temporarily reduced due to a fault or load change or other problem in the grid, WTGs are needed to be capable of LVRT. The seriousness of the voltage sag based on the duration and the voltage level it reduces to. In United States of America, LVRT requirement is specified by the Federal Energy Regulatory Commission (FERC) in Appendix G of its Order No. 661, on June 2, 2005 Large Generator Interconnection Agreement was published.

A WTG is needed to remain working at the time of grid fault as shown in Fig. 5. NERC put forward more strict needs for WTGs to stay online even when the grid voltage decreased to 0 V for a certain cycles. At the time of unbalanced voltage sags, the grid codes needs wind turbine system to decrease the active power and give reactive power to provide assistance to the grid till the grid gets back its usual condition. In existing Wind Turbine Generator system (Fig. 1) when faults or disturbance happens in the utility sides, the WTG voltage at the ac output terminals will fall. The inverter output power can be randomly decreased. But the generated Wind

Turbine Generator power cannot be decreased at the exact moment. This makes an energy difference between the power generated by the Wind Turbine Generator and the power given to the utility side.

The mismatch in the energy will creates a surge in the voltage at the dc-link capacitor. An extremely high voltage may destroy the capacitor and the power equipment's. These kinds of problems should be defeated while combined with LVRT capability. One of the ways to decrease the voltage surge is by putting the extra energy into a dc-link chopper or bleeder resistor as represented in the Fig. 6. If the energy difference is high, then the chopper rating or bleeder circuit rating should be large enough.

Fig. 7 represents the energy profile of WTG at fault condition, and with a dc-link chopper-based LVRT capability. The energy evolved from the chopper is high, as the WTG needs a certain period to do the pitch control attain low power position. At the moment, there is a high chance of the dc-link capacitor voltage to rise up, until the chopper takes the extra power at the time of temporary fault.



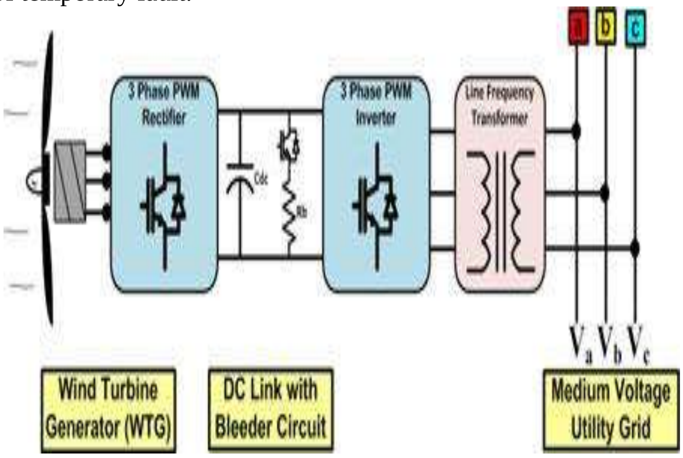
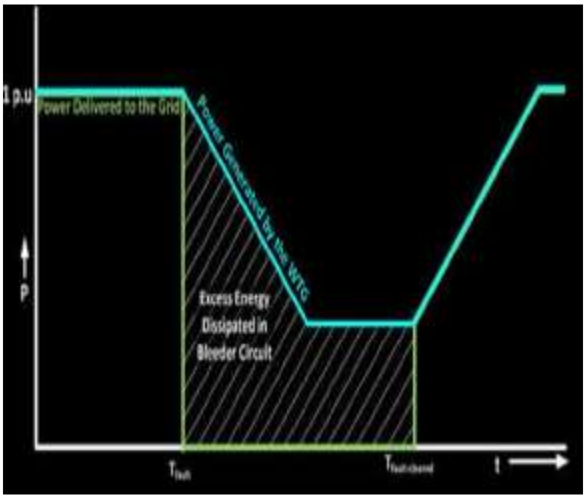


Fig. 5 FERC code for LVRT [24], [25] **Fig. 6. WTG power converter with chopper circuit for LVRT capability [26]**



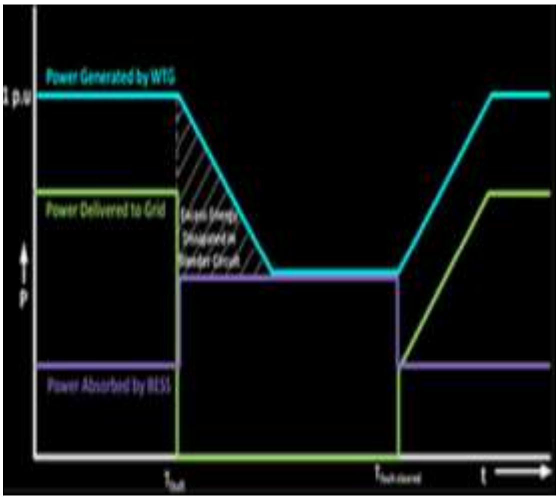


Fig. 7 Energy profile at the time of conventional LVRT **Fig8. Energy profile during LVRT for the proposed topology with dc-link chopper (bleeder).**

TABLE I: SIMULATION PARAMETERS

No	Parameters	Ratings
1	WTG specifications	1.2KV,7-15Hz
2	BESS specification	900V,3MW hr
3	Utility side specification	4.16KV,60Hz
4	Leakage inductance	5%
5	Si- Steel Transformer core	600Hz,0.6T
6	Transformer turns ratio	15:4

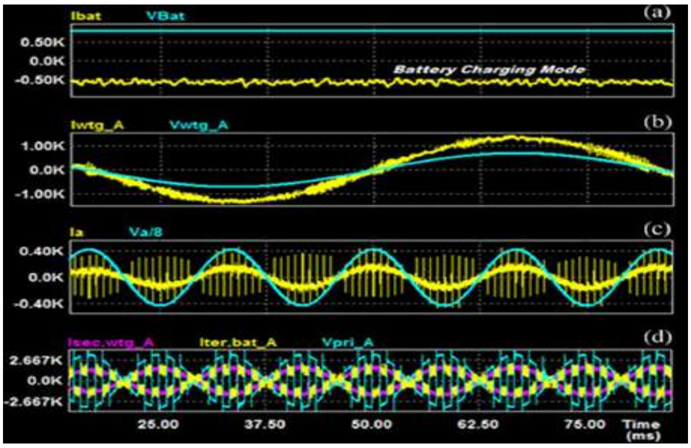


Fig. 9. Charging mode waveforms. (a) BESS current and voltage. (b) WTG phases a current and voltage (15 Hz). (c) Unfiltered utility grid phase a current and 1/8th of utility voltage (scale reduced *for better resolution of current*). (d) Transformer secondary current, tertiary current, and cumulative primary phase a voltage.

In the recommended topology, the BESS is used to decrease the active power to the grid. If BESS does not have needed specification to absorb any more current, the excess energy can be dumped using a dc chopper. The reactive current can be supplied using the BESS during the sag. The amount of reactive power to be supplied is determined by the controller. When the grid is turns back to the normal condition, the phase is decreased to zero and the supply of active power to the grid is continued. When a disturbance happens, it will be detected easily and the BESS system will take the energy from the WTG. If the WTG is working at maximum power and the BESS is not rated for equal power to the WTG, still there is a need of a chopper circuit, but the rating can be too low as the extra energy that requires to be radiated is small. The utility side has an ac– ac converter, at the time of fault it is switched normally. When it used the extra energy the chopper will stop. The BESS gives the needed reactive current to aid the grid until the grid is free from disturbances. If the fault is too serious, the BESS can keep charging the generated power from the WTG until it got the maximum charged and the WTG can be kept working for longer time. This is how the availability of the power and reliability of the system can be taken to an excellent quality.

IV. SIMULATION RESULTS

Fig. 3 shows the topology of PSIM for a 4160 V MV utility grid was simulated. The different system parameters are shown Table I for simulations. The important current and voltage waveforms at charging and discharging mode of the proposed topology of BESS are shown in the Fig 9 and 10 respectively. In Fig. 9(a) we can see that the real power given to the grid is the sum of the power generated or absorbed by the BESS and power generated by the WTG. If the value is negative for current in the battery Ibat it means that the batteries are charging. In Fig. 9(b) the current in WTG Iwtg is shown, the DQ control method is used to regulate the system. The utility grid-side voltage Va is shown in the Fig. 9(c) and the grid current Ia too. Due to transformer current transients the current has some energy spikes.

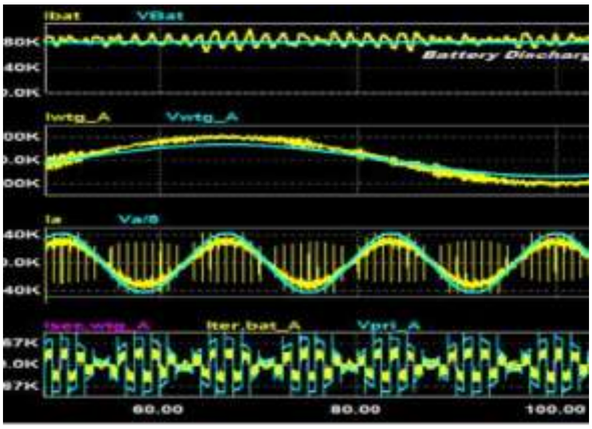


Fig. 10. Discharging mode waveforms (a) BESS current and voltage. (b) WTG phase A current and voltage (15 Hz). (c) Unfiltered utility grid phase a current and 1/8th of utility voltage. (d) Trans-former secondary current, tertiary current, and cumulative primary phase a voltage.

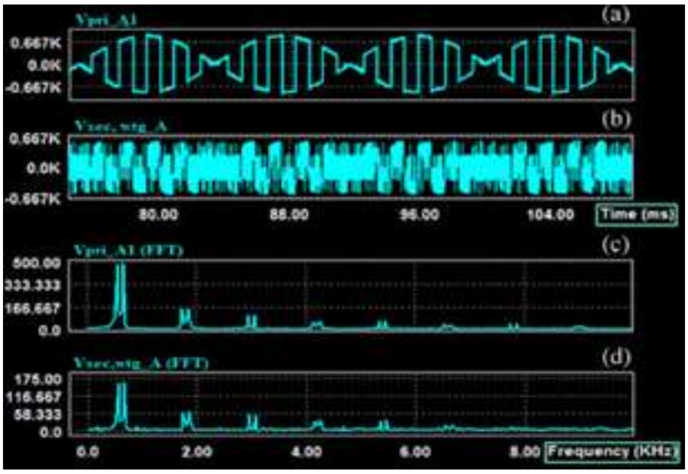


Fig. 11 Transformer phase A voltages: (a) primary voltage, (b) secondary voltage, (c) and (d) FFTs of (a) and (b), respectively.

The utility current Ia is greater compared to the current in Fig. 9(c), the utility will takes power from both the BESS and WTG. The transformer secondary and tertiary currents are in-phase with transformer primary voltage. The peak to peak ripple of the battery current Ibat is regulated within 20%. The transformer level-1 primary and secondary voltages showed in the Fig. 11(a) and (b) respectively. The fast Fourier transforms (FFTs) of wave-forms in (a) and (b) is shown in the Fig. 11(c) and (d) respectively

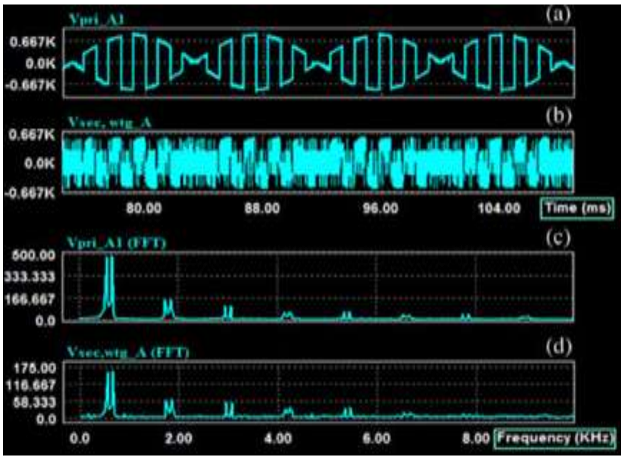


Fig. 12. Variation in grid supply affected by WTG and BESS based on the instantaneous power demand. (a) BESS voltage and current, (b) WTG voltage and current, and (c) utility grid voltage and current.

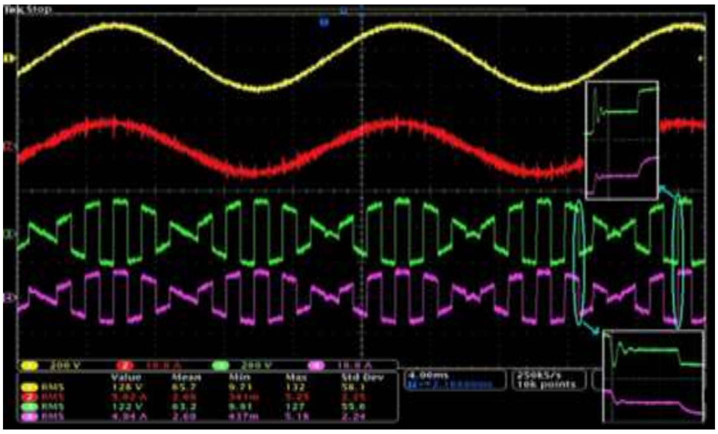


Fig. 13. Experimental waveforms of utility-side ac–ac converter phase A with resistive load along with an MF transformer. Channels 1, 2, 3, and 4 show the grid voltage, grid current, transformer primary voltage, and current, respectively

The variation in utility grid current according to BESS current and power generated in WTG is shown in the Fig. 12. We can notice that the generated power in the WTG is totally used to charge the BESS for a small period of time. The effective power in the BESS, utility, and WTG, are exactly balanced. We can see that the dc-link voltage increases to almost 20%. The operation of the dc-link chopper circuit occurs when the voltage comes at 1800 V and at this time the capacitor voltage will become normal. This is because the absorption of the power from the WTG by the BESS, at this time utility will only take a less quantity of active power. This is why there is no need of tripping WTG even though the fault continues for some duration. The converter can supply reactive power during LVRT.

V. EXPERIMENTAL RESULTS

A transformer of 135 V, 12 A, 600 Hz MF and with a flux density of 0.62 T, with four windings was designed, and the ratings are as shown in the Table II. A transformer of efficiency 97.5% is in the circuit. The efficiency of transformer was found by experiment. The analyze of variation in core loss of transformer with the different type of waveform is the next step. To analyze this, a prototype is built as shown in Fig. 4. An ac–ac converter experimental waveforms is shown in Fig. 13. The experiment is done at a 120 V utility voltage and the secondary side has a resistive load of 1.2 kW, square wave modulation is given at the primary side. The experiment will give an idea about the relative core loss variation for different waveforms, even though it was not possible to determine the actual with the core temperature rise test. For the following operating conditions (1) 600 Hz sine; (2) 60 Hz sine multiplied by 600 Hz square modulation; and (3) 60 Hz sine multiplied by 570 Hz square modulation, using the converter, the loads and rms voltages were applied to the transformer are same. Continues 2 hr. of working is needed to the transformer for each of the previous conditions and thermal camera is used to analyze the core temperatures.

In the case 2 the temperature rise to its maximum value and but in case 1it drops to its minimum value it is shown in the Table III. We can conclude from the test that the transformer has a small value of higher core loss with this voltage of 600 Hz center frequency when examined to 600 Hz sine. In case 3 the waveforms show no saturation distortions. To reduce the core losses we can use a transformer at smaller frequency. The closed-loop control waveforms of current and voltages of transformer primary and secondary with a secondary side dc source as in Fig. 4 is shown in Fig. 14. At 12 kHz the PWM inverter at the secondary-side was switched. The transformer current was regulated at 5 A. in the primary current of transformer there are some high-frequency components it shown in the Fig. 14. By using the filter on the utility grid side these components can be eliminated to get the power factor near unity. The small LC filter can be used because of low energy content. The entire current control scheme will have a time constant to overcome because of the slower ramping up of current when analyzed to voltage.

The transformer secondary voltage produced by the PWM switching is also shown in Fig 14. The product of square PWM and sine PWM is the secondary voltage. The simulation waveforms are almost same as the experimental. The current control step response for a 50% decrease in the primary current reference and with the utility grid and transformer primary voltage waveforms is shown in the Fig. 15. We can notice that at the middle the transformer current decreases to half (channel 1).

VI. CONCLUSION

In this paper a new MV WTG–BESS with interconnected grid converter system, for the proper isolation in a three-port configuration a MF-link transformer is used. The ac–ac converters, PWM rectifier, and inverters are the key idea of the system and the most important equations for the voltages are based on these parts. The total system simulation based on a 2 MW WTG–BESS system, the simulation results were compared with the waveforms from experiment done on the prototype. For the MF transformer Thermal analysis was done. To enhance system efficiency of the system an LVRT method was introduced. Lesser size and weight is main advantage of the proposed topology. High quality power delivery can be produced from this economical system. Amorphous, ferrite, or Nano crystalline core transformer can be used to get the transformer-link frequencies above 2 kHz. With the suitable selection of the core frequency for a certain voltage waveform, the transformer efficiency can be enhanced. Works in Future contain the experimental results on the total system with the analysis of the system in LVRT, voltage swags, etc.

TABLE II

MF TRANSFORMER SPECIFICATIONS

PARAMETER	VALUE	UNITS	PARAMETER	VALUE	UNITS	PARAMETER	VALUE	UNITS
Ae	2.00	ADJ.ST.	K3	0.749		Ww	0.203	m
AeAc	12.48	REQ'D	K2*K3	0.235		CoilW	0.19	m
AeAc	8.00	SQ.ST	VA_tot	6648	VA	MLT	0.232	m
AeAc	16.00	ADJ.ST.	Bm	0.623	T	VOLT/T	1.92	V/T
Wwt	2.5129	Kg	Bac	0.623	T	SkinD	0.003	m
Cwt	5.289	Kg	Closs	34.98	W			
Wvol	0.0012	Cu.m	Wloss	40.01	W			
Cvol	0.0008	Cu.m	Trise	79	deg C			

TABLE III

INCREASE IN MF TRANSFORMER CORE TEMPERATURES

CASE	(i) 600Hz sine wave	(ii) 600Hz sine wave X 600Hz square PWM	(iii) 600Hz sine wave X 570Hz square PWM
Start- Core T(◦C)	27.5	26.6	26.1
End- Core T(◦C)	39.7	41.1	38.8
Variation- Core T(◦C)	12.2	14.5	12.7

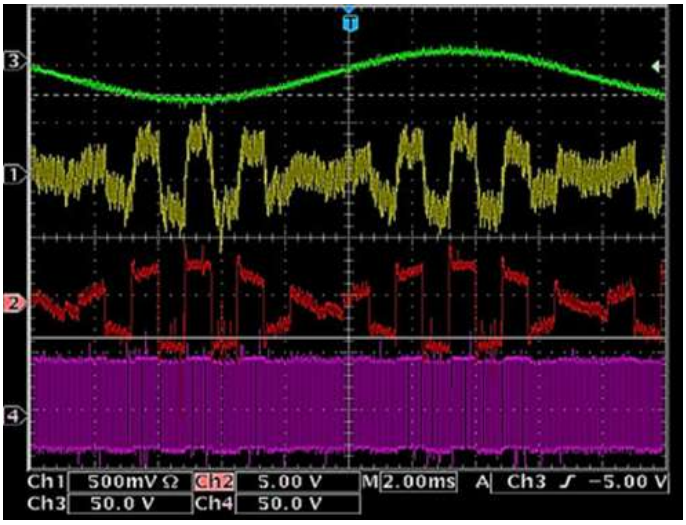


Fig. 14. Experimental waveforms of MF transformer's (Ch.1) primary current, (Ch.2) primary voltage, (Ch.3) utility input voltage, and (Ch.4) transformer secondary voltage, with a prototype setup as in Fig. 4

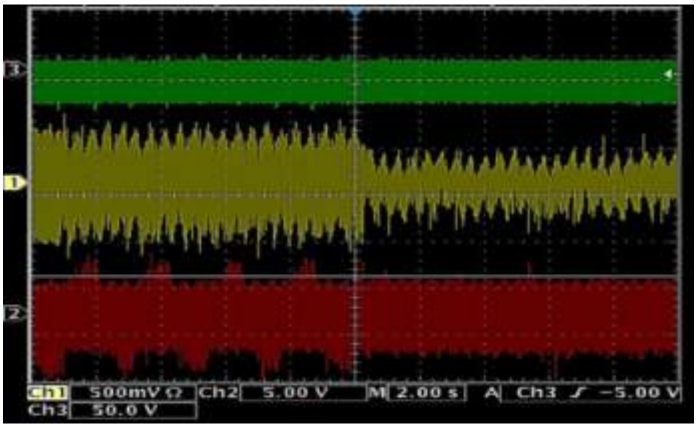


Fig. 15. Experimental waveforms of (Ch.1) primary current, (Ch.2) primary voltage, and (Ch.3) utility grid voltage during a 50% step change in reference of grid power.

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