Fuel Cell Power Conversion Enhancement using Fuzzy Based Soft Computing Technique

Durgam Kumaraswamy and B. V. Sanker Ram

Department of EEE, SVS Institute of Technology, Warangal – 506015, Telangana, India; Kumaraswamydurgam7@gmail.com, bvsram342@yahoo.com

Abstract

Objectives: The aim of this paper is to minimize power losses of device used for power conversion by new converter topology with the fuel conversion is taken as a distributed generator. **Methods/Statistical Analysis**: A set of soft-switching techniques is suggested for a full-bridge forward topology. A special modulation sequence is improved to reduce conduction loss whereas upholding soft switching characteristics in a MOSFETs and soft transitions in output rectifiers. Lastly to decrease conduction losses of a devices owing to its fast acting nature and stable operation by fuzzy controller. **Findings**: In this paper, we have tried to delineate minimization of conduction losses using fuzzy based controller for new converter topology. It will enhance conversion efficiency and voltage regulation. The transformer used to reduce stress on diodes in rectifier and to diminish the circulating currents. The proposed modifications showed an significant efficiency gain under certain operating circumstance. For instance, an efficiency gain of 3%-4% in a power converter with an overall efficiency of 90% provides an enhancement close to a 30%-40% in the thermal management of the power stage and it allows the uses of low cost power semiconductors and Heatsinks. This can be deliberated as an exceptional development to power density and cost of power conversion stage, where as maintaining the simplicity of a full-bridge topology. In addition to, efficiency gains resulted in the increase of fuel savings under operating circumstance by retaining proposed soft-switching techniques. **Application/Improvements:** The fuel cell applications hold numerous topology and it has a group of DC converters and AC inverters and which are essentially used in fuel cell systems for portable or stand-alone applications.

Keywords: Fuel Cells (FC), Fuzzy, Power Conversion Enhancement, Soft Computing Technique, Voltage Regulation

1. Introduction

Fuel Cells (FC) are power sources which transform electrochemical energy into electrical energy with low emissions, high efficiency and quiet operation. A basic proton exchange membrane (PEM) single-cell arrangement is accomplished to produce an unfettered voltage under 1V and it comprises of two electrodes (cathode and anode) linked by electrolyte¹. The output current ability of a single cell is based on the effective area of the electrode and several single cells are linked in series to form a FC stack. Owing to the mechanical challenges related to stacking single cells, typically FC are high current power sources, low-voltage and can constantly run whereas reactant is fed to the system².

*Author for correspondence

Numerous methods were used to identify DC-DC isolated power conversion for FC power sources on the basis of push-pull, full bridge and current-fed topologies. An FC power converter created on voltage doubler is presented, which can be used as phase-shift modulation to regulate the power flow over the transformer leakage inductance³ and this topology verified to be fewer efficient than other custom topologies⁴, but represent the benefits of the low component count. An FC inverter assembled on a conventional push-pull DC-DC converter has features such as DSP control, low cost and low component count⁵. A modular construction is represent to improve reliability and scalability based on the push-pull topology⁶. An advanced current-fed version of push-pull topology have been described as a part of grid coupled inverter system^Z. An identical current-fed push-pull topology is hired in step-up resonant converter offers high voltage-conversion ratio⁸. A full-bridge forward DC-DC converter with a full-bridge rectifier is presented⁹. This will be a very robust topology while operates at zerovoltage switching (ZVS) method and symbolizes and symbolizes an industry standard in various applications, such as telecom power supplies (high input voltage). A three-phase version of full-bridge forward converter is lately proposed¹⁰ based on Δ -Y transformer linkage and clamp circuit is used to decrease the leakage inductance and circulating currents. Suggested family of phase-shift ZVS through adaptive energy storage was also projected to upsurge soft switching operating range using supplementary circuits¹¹. In addition to, current-fed full-bridge topologies were offered with low-input ripple current and minimized stress on the input-side switches¹².

Effective FC power conditioning systems needs deal with high input current, low voltage regulation and a broad range of output loading conditions to preserve great effectiveness and low switching stress. When exposed to stringent conditions, full-bridge ZVS, push-pull and current fed topologies were resisted with numerous technical experiments. For instance, upholding ZVS (full-bridge) is challenging because of the low voltage regulation of the FC and extensive range of loading conditions, where as generates unnecessary conduction loss caused by circulating current. Push-pull topology decreases transformer utilization, negotiates magnetizing equilibrium as the power rating rises as well as restricting the potentials of soft-switching process. Current-fed-based topologies requires bulky input inductors, present oscillations made by the interface among parasite (intra winding capacitance, the input inductor and leakage inductance), and it will reduce high-frequency ripple current in the output capacitors because of the nonexistence of filter inductor. The high-input-voltage converters (e.g., connected to the line) have been used to reduce switching losses and deal with a small line regulation, FC power transformation represents inconsistent consequences with low input voltage, low voltage regulation and very high input current. Distinct applications with high input voltage achieved ZVS with low voltage and it does not lead to efficiency gains. The power dissipation in a MOSFET is caused by the output capacitance throughout turn on process and it can be represented as the square of FC voltage. Since FC are low-voltage, high-current power sources and comparative importance of switching losses can be compensated using conduction loss in MOSFETs and it can be represented as i_{fc}^2 .

Uncertainty problems can be solved by fuzzy set theory. An important benefit of fuzzy logic, knowledge symbol is unambiguous by simple "IF-THEN" relations. All conditions are not characterized via simple and well defined deterministic mathematical prototype and it may be more simply handled in terms of a fuzzy-set theory, whereas simple membership functions and rules were used to develop correct results.

Generally, fuzzy sets were effective at several features with some knowledge representation and they are heuristic and subjective, where as neural networks has capacity in machine learning applications. The fuzzy-logic system is modified in three basic elements:fuzzification, defuzzification and fuzzy implication. IF-THEN rules is used to measure degrees of membership in fuzzifier layer. The results is based on the decisions on the input sequence in the form of a linguistic variable and that can be derived from membership functions can be used to predict the fuzzy set, which corresponds to the fitness value and degree of membership. The variables are then coordinated through the specific linguistic IF-THEN rules and they reply of each rule is accomplished over fuzzy implication, the response of each rule is inclined according to impedance or degree of membership to execute compositional rule of inference and the centroid is measured to generate the suitable output.

This paper describes the challenges 1) to 5) by offering soft-switching methods in a full-bridge forward topology. To achieve this concept, special modulation series is recognized to reduce the conduction losses at the sametime this method maintains the soft switching characteristics of MOSFETs and soft transitions in the output rectifiers. Supplementary elements, such as series capacitors and inductors are unrealistic to realize the input current and that are evaded by reflecting them to the secondary circuit to decrease circulating current and to create soft transitions in the switches. These variants are represented in Figure 1 and this figure showed three major alterations suitable for FC power conversion. The proposed method has competence to sustain high efficiency in entire operating frequency in a FC (wide input voltage) under certain loading condition. Comprehensive investigation of the methods for efficiency gains is offered and a phase-shift ZVS topology is used as a reference topology to highlight the presentation improvement and the advantages of the modulation. Experimental results of a 1-kW power converter are offered to confirm the efficiency gains and they discussed the advantages of the modulation and illustrate the soft-switching transitions.



Figure 1. Conceptual schematic and gate waveforms illustrating L z v s inductor reflection to the output of the rectifier (1), right-aligned gate signals for the upper switches (2), and +50% duty cycles in the lower switch (3).

2. FC Voltage Regulation

This segment concisely examines the regulation features of a polymer-electrolyte FC over diverse operating circumstances, offering the foundation for successful implementation of power conditioning stages. direct methanol FC (DMFC) and PEMFC fit to this category. The factors that provides main contribution to the output voltage characteristics in DMFC are fuel (methanol concentration), fuel flow rate (supplied given to the anode), oxygen/air flow rate (supplied given through the cathode) and operating temperature.

In addition, the output current was an important factor it disturbs the output voltage and later, its output power. The output voltage of DMFC is greatly affected by output current and operating temperature (fuel and oxygen flow rates are closes to optimal value in this case). This significant change in results is indicated in area under polarization curve and output power. As a result, to attain desired output power, it will be mandatory to alter the operating conditions to enhance the area under polarization curve. It should be noted that the state transition from one variation to another variation in polarization curve showed very low operating conditions. The main causes for this performance are higher heat capability of cell and slow mass transport developments in flow fields and electrodes^{2,13}. Though, a fast dynamic response occurs while the output current fluctuates in fixed operating situation. Thus, large current, poor voltage regulation and low-voltage characteristics are emphasized. The same principle can be used for larger electrode areas to produce high current and to enhance quantity of singles cells in series FC stack.

3. Right-Aligned Modulation and Primary Inductor Elimination in the Full-Bridge Topology

The sections were presented in a sequential and conceptual manner that takes steps to increase the effectiveness of full-bridge forward converter. A depiction of powerloss mechanisms in input phase is first offered, then the analysis of output rectifier was done. The proposed FC system is developed by combinatorial effects of softswitching techniques.

3.1 Full-Bridge Input Stage

The conduction loss in MOSFETs are caused by circulating current and high current bulky inductor in a primary circuit were removed by eliminating traditional $L_{\rm zvs}$ inductor in the primary circuit and by imposing a sequence of pulses in upper switches as are demonstrated in Figure 1. In order to demonstrate the gain of the proposed system have proved that conduction losses of commercial MOSFET as a function of duty cycle can be used in hydrogen FC that are available in market. It can be realized that total conduction losses in phase-shift ZVS are significantly larger this losses only connected with power transferred to the secondary circuit. The losses has been calcuated by rms current above switch *M*1 and MOSFET-resistance , which can be described by device temperature

$$P_{losscon} = R_{dson} i_{M1}^2 \tag{1}$$

For instance, IRFB4110 has 3.7 m Ω on 25^oC and 6 m Ω on 100^oC (classic), causing conduction losses of 35W below 75A rms on 100^o C. Once switching losses were examined, the device experiences power lesser than 6.5 W through turn-ON transition caused by its output capacitance C_{oss} while switching was achieved on 40 kHz by $v_{fc} = 22$ V as specified below:

$$P_{losscoss} = \frac{1}{2} C_{oss} F_{sw} v_{fc}^2$$
⁽²⁾

Thus, it may be concluded that in the specific lowvoltage and high-current application, gain efficiency is a resultant from decreasing circulating current in a four switches compensates switching losses, particularly in hefty load settings. However, lower switches were deliberated, but the consequence are surplus satisfactory, as M2and M4 not only helps in low conduction losses, however it also operates in ZVS caused by the alteration (3) in a modulation. Moreover, decrease in conduction interval will also benefits in reducing the copper losses in the windings of the transformer and it favors the utilization of planar magnetic with lower intrinsic leakage inductance towards rise power transfer.

3.2 Output Rectifier Stage

The output rectifiers offer low power losses as a result of reverse recovery and conduction. Meanwhile, output voltage of power converter are greater (i.e., 220 V to supply a single-phase inverter), then the conduction current is naturally few amperes for every kilowatt of output power (i.e., 4.54 A), creating reverse-recovery losses as a dominant factor. Reverse-recovery charge can be represented as a function of forward conduction current (*IF*) and change in current (*di/dt*), along with operating temperature of device. The reverse-recovery losses can be valued using switching frequency (*Fsw*), recovery charge and reversly applied voltage (*V_R*) with peak ringing value as mentioned below.

$$P_{loss} = Q_{rr} V_R F_{sw} \tag{3}$$

Because of reviewed combined effects, theoretical relationship between IF, di/dt, and Q_{rr} in which initial forward current is specified by *IF* 3 > *IF* 2 > *IF* 1. As designated in (3), reverse-recovery losses can be minimized by adjusting *di/dt*[design goal (c)] and decreasing reverse peak voltage V_R created by transformer oscillations [design goal (d)]. For this reason, L_{TVS} inductor is reflected by secondary windings and positioned at the output of respectively upper rectifier D5 and D7 (modification ③). This technique restricts *di/dt* in upper rectifiers, removes reverse recovery current in lower diodes D6 and D8, and decreases considerably by inhibiting zero-voltage state at the secondary circuit. This technique evades instantaneous conduction of D6, D5, D8 and D7, thus decreasing the unwanted ringing that occurred during the primary current matching inductor output current, that results in serious voltage step in secondary circuit that generates ringing, and consequent to electromagnetic interference. In the next section, operation of full-bridge forward converter and the consequence of proposed modifications for

efficiency enhancements were offered in detail above several switching intervals.

4. Operation Intervals and Loss-Reduction Effects

The group of proposed methods, L_{zvs} inductor reflection to the gate signals, output rectifier ((1)) with right-alignment for upper switches ((2)) and +50% duty cycle in a lower switches ((3)) were examined in detail in this subdivision. Figure 1 showed the switching sequence for MOSFETs (S1, S2, S3, and S4) with main waveforms under study. Transition intervals have been overstated for clear view.

4.1 Detailed Analysis of the MOSFETs Waveforms

The waveforms of MOSFETs *S*1 and *S*4 and there corresponding body diodes *D*1 and *D*4 were illustrated in Figure 1 through full-cycle period, comprising *G*1 and *G*4 as gate signals, *vS*1 and *vS*4 as drain to-source voltages, *iM*1 and *iM*4 were n-channel currents and their body diodes were *iD*1 and *iD*4.

As it can be realized that contrast to phase-shift ZVS, the proposed methods inhibit reduces the circulating current in the transformer circuit throughout the MOSFETs, and permits power transfer through conduction interval. This is the main requirement in high-current applications and low-voltage wherever as conduction loss is considerable and the outweigh switching losses will be moderate with switching frequencies. In addition to, +50% duty-cycle modulation series confirms zero-voltage transitions in M2 and M4 MOSFETs. The gains defined in this unit were further improved in the output rectifier as designated in the forcoming sections.

4.2 Output Rectifier Waveforms

To complete the investigation of efficiency gain waveforms and output rectifier. The current waveforms and voltage for *D*7 (upper) and *D*8 (lower) diodes were offered in Figure 1, wherever as reverse-recovery time and conduction losses can be determined.

In summary, the waveforms for proposed soft-switching method revealed the following enhancements.

- The auxiliary inductors *La* and *Lb* forms the current waveforms of *D*5 and *D*7 through reverse recovery. Hence, inductor values can be chosen as valid parameter to attain desire *Q*rr in upper diodes and, henceforth, it will regulate total reverse recovery power losses.
- Diodes *D*6 and *D*8 has capability to neglect reverse-recovery losses and which dissimilar to phase-shift ZVS topology, which is described using near-zero forward current while reduced reverse voltage is applied.
- The existence of *La* and *Lb* minimize oscillations and peak reverse voltage supplied to *D*6 and *D*8 which results from transformer ringing.

Transformer oscillation produces unwanted consequence, for example maximum reverse voltage rating for diodes, over voltage between windings, EMI and power losses in secondary snubber circuits. The concept used to avoid zero-voltage condition on secondary windings of the transformer was addressed by avoiding instantaneous conduction of *D*5, *D*6, *D*7 and *D*8. Consequently, turn-ON pulse is moderately reflected by secondary windings of transformer as the converters were operated in intermittent conduction mode. Therefore, the oscillations were minimized in any load condition.

4.3 Frequency Response and Dynamic Behavior

The frequency response of control-to-output characteristic is a buck-derived topology and which are controlled using transfer function of output filter (L) and once the converter is activated in phase-shift ZVS, series inductance is needed towards restrict the current change in primary circuit to create soft transitions in switches¹⁴. This drawback, minimizes the actual duty cycle reflected by secondary circuit. consequently, it will affect controlto-output characteristic. Thus, an artificial dumping effect is produced in the frequency response curve using series inductance that makes control-to-output characteristic peak softer at resonant frequency of filter circuit. Closed-loop operation with conventional compensation, artificial dumping does not has perceptible effect in gain and phase margin. The same performance is experienced in the proposed methods that are exploited by conventional compensators, hence, producing dynamic response related to phase-shift ZVS.

This study is used to simplify the evaluation process of efficiency, multiple measurements were implemented by closed loop controller with steady-state operating conditions. The controller was recognized by inner current loop (inductor current) and outer voltage loop. Verification of a waveforms and relative efficiency measurements were described in the resuting unit.

5. Simulation Results

5.1 Validation of the Waveforms

A entire switching cycle in M4, M1, D8 and D7 were calculated in medium loading condition to confirm the waveforms. To enable visualization, switching frequencies were fixed in 40 kHz. Figure 2 showed the waveforms of MOSFETM1, comprising drain-to-source voltages and gate and secondary transformer current. It may be realized that MOSFETcurrent originates at zero (ZCS) at the starting of *T*1 and gradually ramps up till it extents the current level of output-filter at the starting of *T*2. The MOSFET turns off in *T*3, restricting the level of interval conduction to T1-T2. The conduction interval of body diode D1 can be realized in T11, which returns the leakage inductance energy toward the input dc bus and prevents circulating current in primary circuit. The lesser energy in leakage inductance is clamped and absorbed using input capacitors. The low MOSFETM4 waveforms were illustrated in Figure 3, where zero-voltage transition in turn-ON can be viewed at the starting of T11. Subsequently, at the opening point T4 and M4 turns off. In addition to this D4 has soft-switching transition capacity in T5. The conduction phase in M4 is identical to M1, demonstrating minimized conduction losses.



Figure 2. Upper side MOSFET S1 waveforms in the proposed modified topology under medium loading condition: drain-to-source voltage (Ch1), gate-tosource signal (Ch2), and transformer-secondary current (Ch4).



Figure 3. Lower sideMOSFETM4 waveforms in the proposed modified topology under medium loading condition: drain-to-source voltage and current (Ch4).

To estimate phase shiftZVS converter operation, inductor Lzvt was incorporated and La and Lb were eliminated along with gate-to-source signals and secondary current waveform. It may be realized that turn-ON transition arises in (T1) interval and the conduction is

prolonged till the end of (*T*6). As defined by the investigation of conduction losses, the conduction interval produces unwanted circulating current. MOSFET M4 (lower side switch) offers relative performance along with circulating current.

Concentrating on rectifier stage, the upper outputrectifier D7 waveforms with proposed methods were illustrated in Figure 4. The turn-OFF shift in forwardbiased blocking was demonstrated in interval T1. The result of *Lb* and *L*lk can be obtained by current transition, causing reasonable reverse-recovery losses at the starting point of *T*2. The end of *T*7 interval relates the time when current in *Lb* matches with the current in output-filter inductor *L*. In *T*8 , the slope of *iD*7 is mostly caused by *L*. The conduction interval is well-defined from *T*7 to*T*1



Figure 4. Upper side diode medium loading condition.



Figure 5. Upper side diode *D*8 waveforms in the proposed modified topology under medium loading condition.

of subsequent switching cycle. As it can be viewed that transformer oscillations were small and but it experiences fast damping at the starting point of T2. Only an initial peak was experienced caused by the influence of stray inductance in current path and Lb. This offers a clear suggestion that proposed procedure needs small local snubber linked from D7 cathode towards L input terminal, contrast to the renowned bulky snubber in ZVS circuits.

The results of proposed modifications is appreciated from experimental waveforms which was represented in Figure 5. Owing to interleaving result of *La* and *Lb* in *T*3-*T*5 interval, diode *D*8 experienced fast transition from conduction current to zero current. In the starting point of *T*7, converter input voltage has been moderately reflected by secondary windings and blocks. Instantaneously *D*8 creates negligible reverse-recovery losses. Because of the blocking transition offers reasonable ringing at the starting point of *T*7 whereas upper diode current *iD*7 ramps up. Then this results were compared to analyze the performance of phase-shift ZVS, which was depicted in Figure 5, diode D8 produces unwanted reverse-recovery losses at the starting phase of T8, where small negative-current peak was obtained by the effect of Qrr. As determined by analysis, ringing peak voltage in D8 is too large and this will increase the reverse-recovery losses and requires bulky snubber.

Eventually, to validate input current is positive, a rudimentary obligation is needed in FC power conversion, Figure 4 depicted the input current of converter and transformer input voltage in medium load condition. As determined by analysis, current rests positive throughout all the switching intervals.

5.2 Comparative Efficiency Measurements

The combined conduction losses and switching for proposed soft-switching methods were offered. A phase-shift

Parameters	Value limits
V _{fc}	18-40V
V _o	220V
L	1.33mH
D _a , L _b	10uH
С	680uF
C_{i}	4400uF
F _{sw}	40-100kHz
T/f primary turns N _p	2
T/f secondary turns N _s	26

Table 1.Converter parameters

Zero Voltage Switching is used as reference topology for relative estimation. Power transformer, drivers, power devices, fan, heatsink, output filter and dead-time insertion were used to verify a fair comparison and it was shown in Table 1. The main objectives of experimental efficiency measurements is to demonstrate the gain efficiency of proposed modifications moderately than absolute measurement of converter efficiency. The efficiency measurement of connections, power switches, printed circuit board and magnetic parts does not contain losses in drivers and controller. For Zero Voltage Switching operation, secondary snubbers and Lzvt inductor were involved, while eliminating La and Lb. Numerous tests were implemented for different input voltages vfc = 18, 25, and 30 V in variable load conditions (50-1000Watt) for power converters. The outcomes were illustrated in Figure 2, and it demonstrates the efficiency as a representation of output power to input voltage in 3-D plot. That is very significant to focus that efficiency characterization in powerconverters is usually achieved by fixed input voltage, FC power conversion needs the usage of polarization curve to lax voltage regulation. Hence, surface efficiency measurement offers enhanced means for comparison. The efficiency profile attained with proposed soft-switching methods, mentioned to be Modified in the figure which is represented with circle markers, whereas phase-shift ZVS was demonstrated with star markers. It may be realized that proposed modifications provides significant gain efficiency in whichever operating condition. For instance, gain efficiency is 3%-4% in power converter with 90% overall efficiency offers an enhancement close to 30%-40% in thermal management of power stage and it permits the usage of low cost power semiconductors/ Heatsinks. It can be deliberated as an superb development towards power density and power conversion stage, whereas preserving the simplicity of full-bridge topology. In addition to gain efficiency results in amassed fuel savings in any operating circumstance such as light, medium and heavy by utilizing the suggested soft-switching methods.

6. Conclusion

This paper describes the minimization of conduction losses by fuzzy based controller for new converter topology. It will improve voltage regulation and conversion efficiency. The transformers were employed to minimize the stress on diodes and to reduce circulating currents.

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