II. RENEWABLE AND ALTERNATIVE ENERGY SOURCES AND BIOFUELS

ALTERNATIVE APPROACH TO SMALL SCALE PHOTOVOLTAIC SOLAR POWER AND ENERGY STORAGE

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Abstract. Photovoltaic solar panels remain one of the most commonly available avenues for acquiring renewable energy for small-scale end users but despite their promising potential their implementation continues to remain outside the realm of possibility for most. The combination of high upfront costs, long payback periods, and complex installation requirements results in a disincentive to purchase the technology and relies on significant appeals to morality as a driving force as opposed to purely economic incentives. An alternative implementation of photovoltaic arrays for small scale use combined with grid power supplement is herein proposed that better matches energy consumption profiles in the household and seeks to reduce cost and complexity. The system comprises a hydronic thermal storage system acting as hot water supply, furnace, and air conditioning for power regulation and distribution in combination with electrical distribution to home appliances using minor modification to the power supply. Currently used batteries, charge controllers, and inverters are eliminated and replaced with a single specialized outdoor central air-conditioning condenser unit that distributes electrical and thermal energy but would not supply electricity onto the grid. Examination of minor electronic modifications on common switched mode power supply topologies has found that regulation of a wide range of variable voltage solar electricity input is currently possible and does not cause overheat or other harm to the power supply. The proposal provides a workable solution to alleviate financial and technical burden on the individual and promotes the vision of a 100% renewable energy society while working within economic constraints.

Keywords: energy storage, solar power, lithium battery, switched mode power supply, electronically commutated motor, air conditioning, variable refrigerant flow

ABBREVIATIONS

AC – *alternating current*
AFCI – *arc fault circuit interrupter*
AHU – *air handler unit*
DC – *direct current*
ECM – *electronically commutated motor*
EEV – *electronic expansion valve*
EMI – *electromagnetic interference*
HE – *heat exchanger*
HFT – *high frequency transformer*
HVAC – *heating ventilation and air conditioning*
IGBT – *insulated-gate bipolar transistor*
LSRE – *large scale renewable energy*
MEL – *miscellaneous electric load*
MOSFET – *metal-oxide semiconductor field-effect transistor*
MPPT – *maximum power point tracking*
PFC – *power factor correction*
PWM – *pulse width modulation*
SMPS – *switched-mode power supply*
SSRE – *small scale renewable energy*
TMV – *thermostatic mixing valve*
VRF – *variable refrigerant flow*

1. INTRODUCTION

1.1 Current Market and Approaches

The success or failure of a technology is largely dependant on its marketability, where solar energy systems struggle to gain traction on the consumer market. A new preliminary small-scale photovoltaic energy system is proposed using electrical thermal storage by more optimal use of household HVAC equipment and modified electric appliances operated as a unified system that is better able to address the concerns and economic constraints of individual consumers. The market for solar technology has seen steadfast growth in terms of investment, research, and innovation within the past decade but the application of such technologies remains stifled for small scale use, requiring strong federal subsidies to drive the market [1, 2]. Fig. 1 displays the per annum growth of the US solar market over the past decade showing very strong initial growth encouraged by strong subsidies followed by a persistent decline in all sectors with waning subsidies suggesting the renewables market continues to be highly government dependent to present day.

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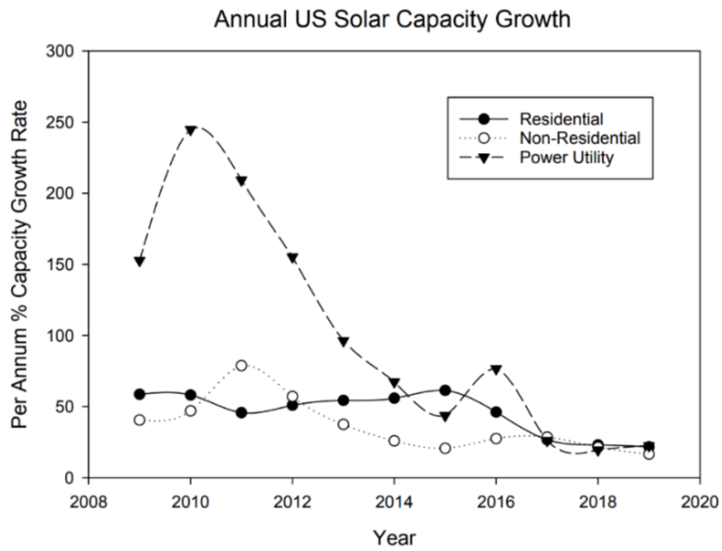

Fig. 1. Growth trends of the US solar market [3].

Current generating capacity of solar energy for the 2019 year stands at 14,385 MW_{DC} non-residential, 15,850 MW_{DC} residential, and 45,765 MW_{DC} power utility with the sum of all current solar power contributing 1.8% of overall power generation and 10.3% of renewable energies in the US [3, 4]. Helping to drive the market has been a sharp decline in solar panel costs of approximately 70% over the past decade largely due to economies of scale in greater factory sizes, and both public and private research and development contributions [3, 5]. While the solar energy market continues to experience growth, it is still a far cry from replacing non-renewable energy sources entirely in the years ahead and future growth trends remain uncertain. A recent examination of public opinion in the US on residential solar power installation reveals economic factors remain the leading cause of concern with 59% of respondents citing high costs as the primary obstacle in pursuing installation. The study also concluded that reducing electricity bill costs was the primary drive to consider such solar installations with 69% of respondents citing this as a key factor [1].

A major expense in current SSRE design comes from the requirement for batteries necessary for energy storage and regulation. Battery lifespan poses a challenge where practical function is accomplished with $LiFePO_4$ batteries with an average lifespan of 29.4 years as compared to 3.0 for NiCd, 6.0 for flooded lead-acid, and 6.8 for lead-acid gel which would necessitate multiple replacements over the lifespan of the photovoltaic cells [6]. Over-reliance on lithium-based batteries may also pose future challenges where the scarcity of the metal with global reserves of 17 million metric tons [7] could theoretically produce 1.42 billion cars assuming an amount of 12 kg of lithium per vehicle [8], less so when larger vehicles and alternative uses are factored in. Consider then the number of cars in only a few select developed regions; 111 million cars in the United States [9], 62 million in Japan [10], 288 million in Europe [11], and 270 million in China where China continues to maintain a very strong year over year increase in road vehicles of roughly 12% [12]. It could be the case that sudden demand for electric vehicles could overwhelm supply ability and lithium battery prices could increase substantially.

1.2 Alternative Approach

To develop an alternative approach to SSRE it is necessary to first assess the expected energy demand and distribution in the home. Some loads are not ideal for consideration in this SSRE proposal and are best left to grid power. Electric lighting for example has significantly reduced in power requirements on the order of less than 10 W per bulb using LEDs, conversely operation of a clothes dryer occurs in only short duration but is quite taxing on the generation ability of SSRE systems. A breakdown of average household energy use is seen in Figure 2 where heating, ventilation, and air conditioning (HVAC) and water heating take up 70% of energy consumption. In addition, the proliferation of power hungry miscellaneous electric loads (MEL) such as televisions and desktop computers accounted for 143 TWh used in the 2017 year, or about 10% of total US electrical consumption [13]. With this knowledge it is obvious then that thermal energy management requires priority to achieve the vision of a 100% renewable energy society being considered in many localities [14 - 17]. Therefore, thermal energy storage and utilization is preferential in any such SSRE design and electrical energy supply should act in a more supplementary role.

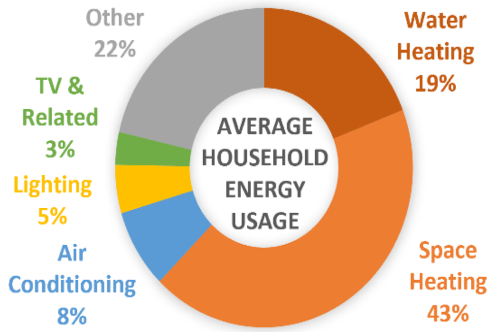

Fig. 2. Average total energy consumption proportions of US households in year 2015 (electrical and hydrocarbon fuels) [18].

2. PROPOSAL

Installation of the solar panels would require selecting the correct combination of parallel-series connections to achieve an appropriate high voltage. The HVAC equipment would be designed to perform maximum power point tracking (MPPT) operations by distributing solar power to MELs from a specialized central outdoor air conditioning condenser unit and dumping remaining excess energy into thermal. The circuitry necessary for the distribution of the DC power can be kept simple using MOSFET switches to direct the solar DC power flow to household loads and regulate power distribution between loads with use of pulse width modulation (PWM). The integration of such a system into a typical North American household electrical wiring scheme is shown in Fig. 3.

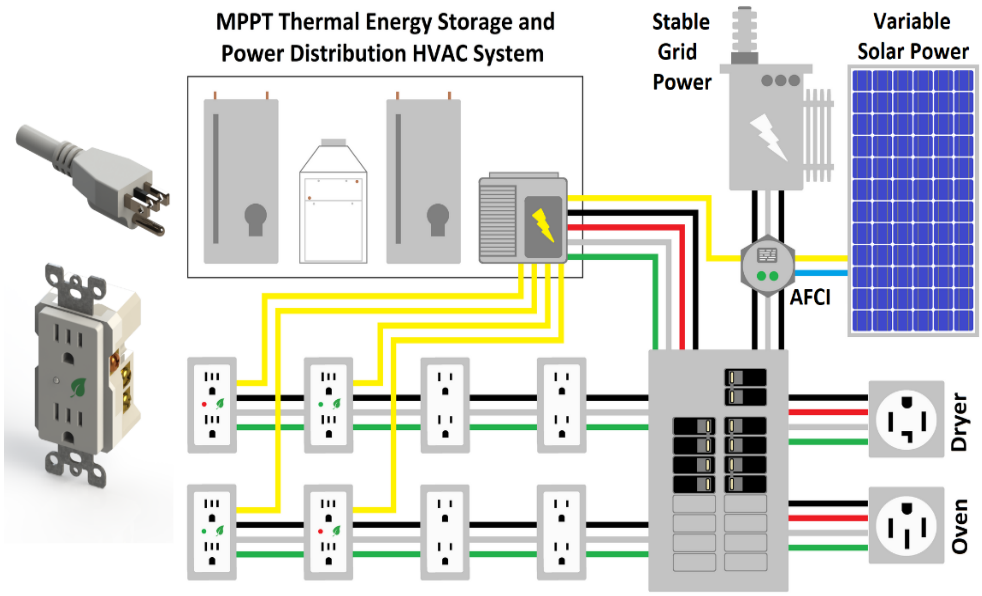

Fig. 3. Integration of proposed SSRE solar power system into North American style single phase 120/240 V AC electrical system.

The proposed system in Fig. 3 would require additional retrofitted wiring in the household adding some complexity to installation however installations in new construction could include the necessary wiring with minimal added cost to construction. The additional wiring (yellow) would deliver high voltage variable DC to specialized receptacles also powered with standard AC grid voltage to power MELs. The neutral wire (light grey) would act as the current return path for both line voltage and high voltage solar, where the common wire from the solar array (blue) would be connected to the neutral and grounded. Such a system carries the risk of the line voltage and solar voltage encountering one another from any number of abnormal situations which would result in damages and unsafe conditions to anyone connected locally to grid voltage fed from the same supply transformer. For this reason, an Arc Fault Circuit Interrupter (AFCI) device is necessary to break the main line and solar voltage feeds to the building in fractions of a second in the event of an anomaly. Some improvements to wiring specifications may be needed to operate safely where insulation voltage ratings should be set to a 600 V rating as opposed to the usual 300 V rating for standard 120/240 V_{AC} wiring. The neutral wire used on dual voltage source circuits may also need to be increased to a thicker gauge to handle the potential for increased current loading. While higher voltages would be encountered within the wiring system, they would remain low enough to comply with installation standards such as those of NEC 690.7 and IEC 60364-7-712.

Typically designs of a solar power system utilizing thermal energy storage take a combined photovoltaic-thermal approach whereby thermal energy directly from the sun is extracted using a liquid or gas heat carrier flowing through channels built inside the solar array [19]. Similarly heat pumps have been proposed using a refrigerant gas to move heat absorbed from sunlight and redirect the heat to thermal storage [19, 20]. While the designs no doubt provide an efficient collection of total solar energy, the complexity to construct and install such panels comes with much higher total cost. Even where payback periods are found to be one-third less [19] individuals unwilling or incapable of spending such large sums of money may be discouraged from purchase. Such thermal collection systems may prove troublesome in seasonal climates with long cold periods as well, where efficient thermal collection would require additional vacuum separated components further complicating construction. The proposal instead uses a much simpler less common electrical thermal storage design capable of using ordinary photovoltaic panels without thermal collection. Such designs have been tested and found to function adequately in lower income Northern climates providing a simple supplemental energy source for heating while maintaining thermal isolation from the outside environment [21, 22]. The proposal expands on this by providing a solution capable of also competing with more standardized battery-inverter systems on the trend that photovoltaic technology will continue to drop in price allowing for an alternative low-cost market entryway.

2.1 Dual-Input Electrification Appliances

Under this proposed system, power to dual-input electrical source MELs would be switched seamlessly from the grid to raw variable DC voltage provided by photovoltaic solar cells and vice versa within the power supplies of the MELs. The installed solar panel system would be required to operate in a high voltage mode at a maximum possible voltage of 400 V_{DC} to adequately integrate with the power supplies of the MELs. The MELs could use modified four pronged plugs based on the NEMA 5-15 standard to engage with specialized wall sockets allowing for electrification with solar or grid electricity but would still be capable of accepting standard NEMA 5-15 three prong plugs as seen in Fig. 3. Attempting to introduce such a modification of standards on the consumer market would ordinarily be quite difficult, however mass installation of the proposed solar thermal energy systems could provide a more favourable entry to market pathway.

The proposal would specifically target MELs using switched mode power supplies (SMPS). The SMPS represents a fundamental electronic system designed to convert AC line voltage into the necessary DC voltages for the internal subsystems of a MEL. An inspection of the circuitry within a SMPS reveals commonly observed topologies consisting of an electromagnetic interference (EMI) filter and rectifier, active power factor correction (PFC), and high frequency transformer (HFT).

Of particular interest within the SMPS are the PFC and HFT circuits, both of which are typically capable of stable output voltage regulation when powered with differing regional AC grid voltage (120 or 240 V AC systems) and frequency (50 or 60 Hz systems). Because of this design, the SMPS can easily be exploited as a means of being powered directly from the unprocessed variable DC voltage provided directly from solar panel arrays. A switch over to rectified AC grid voltage when solar power is insufficient using an arc quenching relay circuit (Fig. 4) or some type of fully solid-state switch circuit would be necessary. Regulation in these circuits is accomplished using high frequency (~100 kHz) PWM control of DC power into a transformer or inductor to meet the desired output setpoint voltage. Active PFC circuits typically contain more complex control than HFT circuits as they also seek to moderate the input current draw over the AC cycle to shape it into a sinusoid and synchronize the resultant current sinusoid to the voltage sinusoid [23]. Addition of the PFC circuit to an appliance is done only to comply with standards such as IEC 61000-3-2 and FCC 47 CFR 15 and therefore might be desirable to manufacturers if it could be used in an alternative manner to generate a useful product feature, recouping the otherwise lost profit from an unavoidable manufacturing expense.

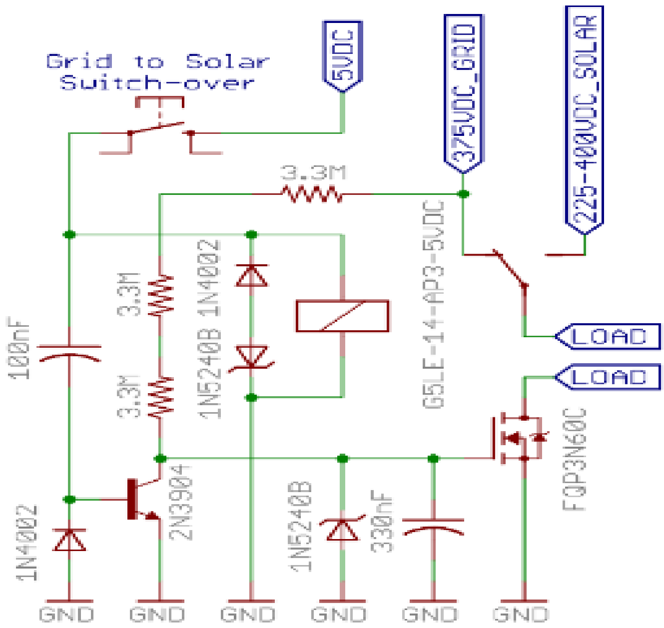

Fig. 4. Arc quenching relay switch-over circuit to be added between EMI filter & PFC or PFC & HFT.

One additional type of SMPS that might be exploited for direct solar power electrification is the power supply of the increasingly popular high efficiency electronically commutated motor (ECM). In this instance the SMPS in the motor delivers power as a high frequency PWM wave that is absorbed by the inductance of the motor core and converted to a lower frequency sinusoidal magnetic flux [24]. By adding an additional set of IGBT switches the motor could rapidly switch between both a grid power bus and solar power bus, using both power sources at the same time. This would be advantageous for household use with the furnace blower as well as central air conditioner compressor and condenser fan.

2.2 Solar Photovoltaic Integrated Heating and Cooling

The proposed hydronic system in Fig. 5 relies on two electrically powered hot water tanks located near an air handler unit (AHU) to store and provide sources of thermal energy. Making use of hydronic systems based around an AHU is advantageous as such systems can be easily externally configured into custom designs using existing devices such as recirculation pumps, valves, and water tanks. The system will take the unprocessed variable solar voltage and determine the proportion that should be downgraded to lower quality thermal energy or redirected for use as mid-quality electrical energy in the modified MELs through algorithmic means. The water heater on the left would act as a traditional potable hot water tank to provide hot water to the building plumbing through a thermostatic mixing valve (TMV) as well as hot water to the AHU as would normally occur in a typical hydronic installation. The water heater located on the right would serve as a means of storing hot or chilled water depending on operation of the system and would operate as an isolated loop of non-potable water. Isolation allows for use without the hazard of Legionnaires disease caused by *Legionella pneumophila* in stagnant water left below 49 °C for prolonged periods of time [25] as well as allowing the possibility of using antifreeze. Not shown on Fig. 5 are the presence of temperature sensing devices needed for the water tank temperatures. Possible operating modes of the system and component states are summarized in Table 1.

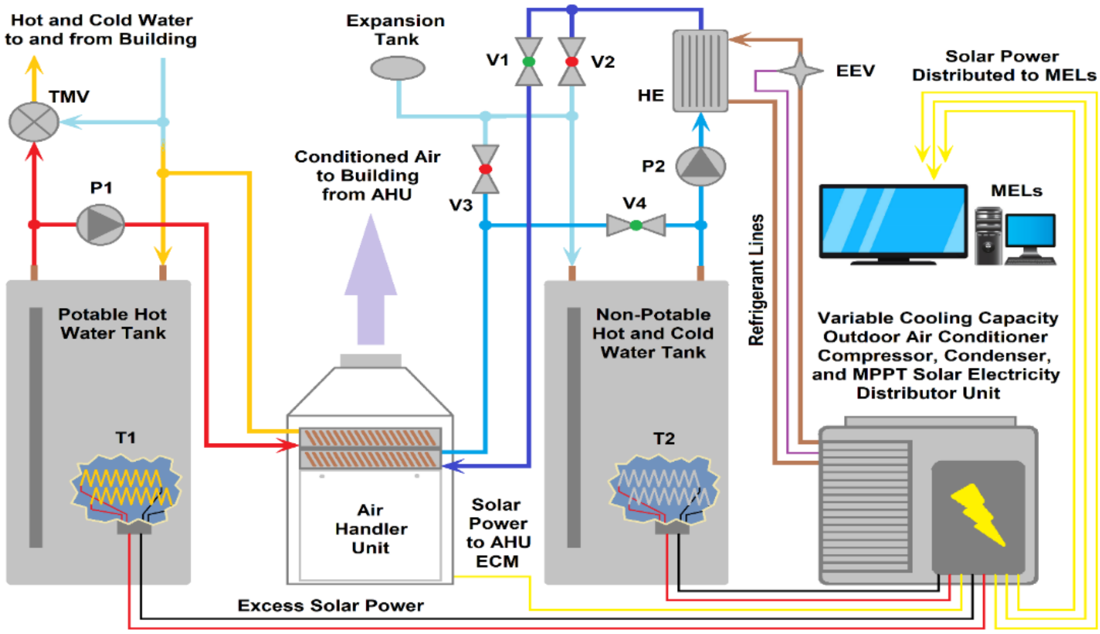

Fig. 5. Proposed solar power enhanced HVAC system using hydronic technology. Both air cooling and heating cycles shown operational for illustrative purposes only.

Table 1. Operating characteristics of thermal energy storage system.

Operating Mode	Component State								
	T1	T2	HE	P1	P2	V1	V2	V3	V4
Air Heating	Heating	Off	Off	On	Off	Closed	Closed	Open	Closed
Air Heating with Supplemental Stored Heating	Heating	Heating or Off	Off	On	On	Open	Closed	Open	Closed
Heat Storing	Heating	Heating	Off	Off	Off	Closed	Closed	Open	Closed
Air Cooling	Heating	Off	Cooling	Off	On	Open	Closed	Closed	Open
Air Cooling with Supplemental Stored Cooling	Heating	Off	Cooling or Off	Off	On	Open	Closed	Open	Closed
Cold Storing	Heating	Off	Cooling	Off	On	Closed	Open	Closed	Open
Tx - Tank Heater; HE - Heat Exchanger (Evaporator); Px - Pump; Vx - Valve									

Conversion of solar energy into air-cooling and chilled water storage can take advantage of an inverter compressor as part of a variable refrigerant flow (VRF) system. The inverter compressor, essentially acting as an ECM, can be powered with grid and solar electricity at the same time and regulate the necessary output of the compressor while simultaneously regulating the ratio of grid to solar electricity to help accomplish MPPT. To apply solar and grid power to the compressor, the inverter electronics will require a more sophisticated switching design using a high frequency interlaced PWM waveform; whereby the interlaced PWM output is composed of a cycle consisting of some proportion of rectified grid voltage, unprocessed solar voltage, and dead time.

Varying cooling capacity by moderating the compressor power requires more stringent control of the refrigerant metering device to maintain adequate high and low side pressures on the system. To perform this task, an electronic expansion valve (EEV) is used to precisely meter refrigerant flow by means of an active electronic control system. A distinction is made here of VRF systems encountered in literature [26 - 29] which typically function in an output regulated multi-zone air heating and cooling role. Where in this case the VRF system is exploited as a variable input load for purposes of MPPT regulation with only a single thermal output heat exchanger (HE) requiring just one EEV control element. The system could also operate in reverse as a heat pump acting as an additional more efficient heat source to the HE.

3. MATERIALS AND METHODS

To confirm the plausibility of the dual-input electrification proposal, simple experiments were conducted on select PFC and HFT circuits to assess their performance in a SMPS as well as design constraints likely to be encountered. Observations of select ECM behaviour were briefly investigated under variable voltage conditions. The tests were meant to act as an assessment of the plausibility of the proposal on a select number of well-established circuit topologies and not a direct comparison of the exact designs of various manufacturers equipment. Testing of the circuits was completed by removing the bridge rectifier from the normally AC powered circuit and injecting DC voltages directly into the positive and negative connection points on the circuit board of where the bridge rectifier once stood. When present, the voltage doubler circuit was turned off by setting the selector switch to the 240 V_{AC} setting. DC voltages for the experiments were produced using two 300V_{DC} 4400μF capacitors placed in series which generated a simple low ripple DC power supply regulated with an AC variable transformer. In all cases, assessment of the circuits was completed by locking the output of the device to a fixed resistive load, varying the input voltage to the device, and then measuring the temperatures of key power components using NTCALUG03A103G thermistors with 2% tolerance as thermal probes fixed in place with Kapton tape. Output load for testing of the PFC circuit consisted of three 25 W 120 V_{AC} tungsten filament light bulbs wired in series. Testing of the HFT circuits made use of a combination of coiled Nichrome wire along with a BK Precision 8540 electronic variable load operated in constant current mode. Examination of an ECM was achieved by setting the motor to 100% output and connecting the shaft to a 24 cm (9.5 inch) diameter 10 cm (4 inch) wide squirrel-cage blower wheel and associated housing with the air outlet fully blocked. All data points were taken after at least one hour of operation at a given input setting to ensure thermal measurements were taken under steady state conditions. Data was collected using a Greenlee DM-810 multimeter and a Reed R5000 wattmeter. All temperature readings of components were completed in still air at 20±2 °C except for the stator coil temperature measurements in the ECM which were subject to moving air currents produced by the spinning rotor and blower wheel.

4. RESULTS AND DISCUSSION

4.1 Assessment of a PFC Circuit

Examination of the practicality of a PFC circuit for the proposal was conducted using a transition mode boost PFC topology which represents the most common type encountered [23]. The creation of the test circuit was realized using the STMicroelectronics L6562 PFC controller along with a Coilcraft JA4224-AL boost inductor based on the test circuit schematic provided in the L6562 datasheet [30]. An operating window of 75 – 400 V_{DC} was observed for the circuit, though input voltages beyond 370 V_{DC} caused the regulation circuit to shutdown and the output matched the input voltage resulting in a small deviation from the typical constant 400 V_{DC} output. The response time of the circuit was found to be very fast with no output deviations detected with input voltage change on the order of 200 V_{DC}/s which is expected as the circuit must track and correct current anomalies on a 50/60 Hz AC sine wave necessitating a very fast sampling rate.

Thermal assessment of the PFC circuit was undertaken by taking measurements of the boost inductor, the switching MOSFET, and the fast recovery diode. While the MOSFET and diode remain mostly constant in temperature over the span of test voltages from 150 V_{DC} and onward, the inductor temperature is strongly influenced by the input voltage because of increasing currents necessary in the inductor windings as voltage decreases [23]. Operation of the PFC circuit on 120 V_{AC} with the same output load produced an inductor temperature of 99 °C, suggesting that the large temperature range encountered under variable DC is not such a big deal as only the upper bound of temperatures are most important to consider which are not far off from the normal temperature generated under AC power. While the PFC circuit can operate on a voltage as low as 75 V_{DC} the high generation of heat in both the MOSFET and diode suggest the practical lower limit of operation of 125 V_{DC} is more reasonable to avoid premature failure of the semiconductor components. At the higher end of operation as previously noted, when input voltage climbs to 370 V_{DC} the regulation circuit shuts down and the temperatures of the components under examination were found to return close to the ambient air temperature, therefore these data points have been omitted from Fig. 6.

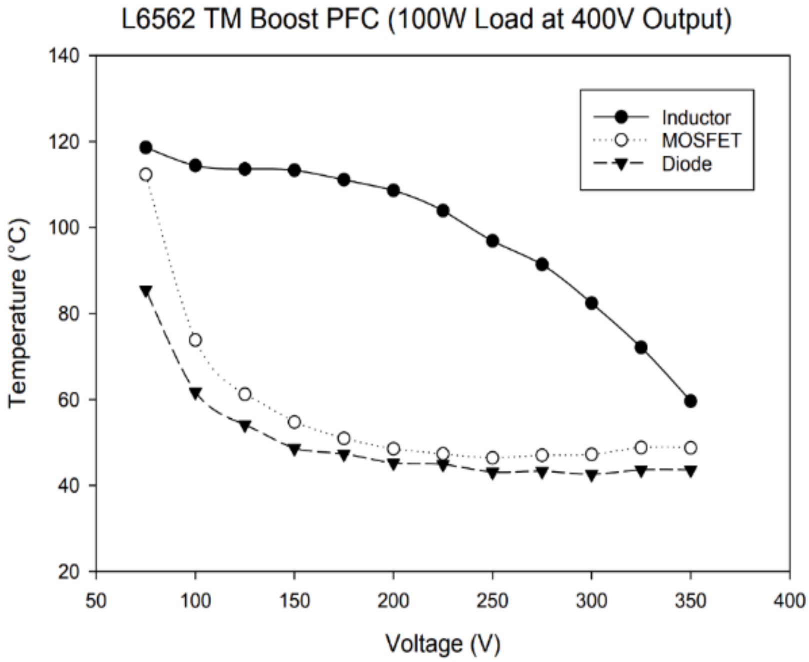

Fig. 6. Thermal characteristics of key components in a transition mode boost PFC driven with variable DC voltage.

4.2 Assessment of HFT Circuits

Three types of the most commonly encountered isolated hard-switched HFT circuit were chosen [31] to assess the applicability of the proposal using basic off-the-shelf single output voltage power supplies. The inlet and outlet properties of these power supplies based on their design and testing can be seen in Table 2 where all three showed a large window of viable DC input voltages.

Table 2. Properties of tested HFT circuits.

Power Supply	Configuration	Output VDC	Output I_{max}	Input VDC_{min}	Input VDC_{max}
LRS-100-12	Flyback	12 V	8.5 A	100 V	400 V
S-100F-12	Forward	12 V	8.5 A	175 V	400 V
S-240-24	Push Pull	24 V	9 A	175 V	375 V

Thermal testing of the HFT circuits focussed on the major heat generating components of the system, these being the transformer, the switching MOSFET(s), and the rectifying fast recovery diode(s). Testing of the HFT circuits was completed at three different power levels given that the circuits may have to fluctuate their output on devices with variable loads, the results of which can be seen in Fig. 7. Thermal characteristics over the input DC voltage range were far better than those encountered in the tested PFC circuit where temperatures remained very close to constant over the entire range of tested voltages. Of particular interest is the fact that in many cases heating effects were reduced with lower voltages, even though the inlet current must be higher to produce the same output. Intuition might suggest that higher inlet current would produce greater heating effects in accordance with Ohm’s law however the data collected suggests that the physical workings of the HFT circuit are more complex than this. This also suggests that depending on the behaviour of the HFT circuit, a high voltage provided by a PFC circuit preceding the HFT circuit may not always be beneficial thermally. Observation of the response time of the HFT circuits showed very fast response similar to that observed in the PFC circuit, where changes in input voltage on the order of 200 V_{DC}/s showed no noticeable effects on the output in all cases.

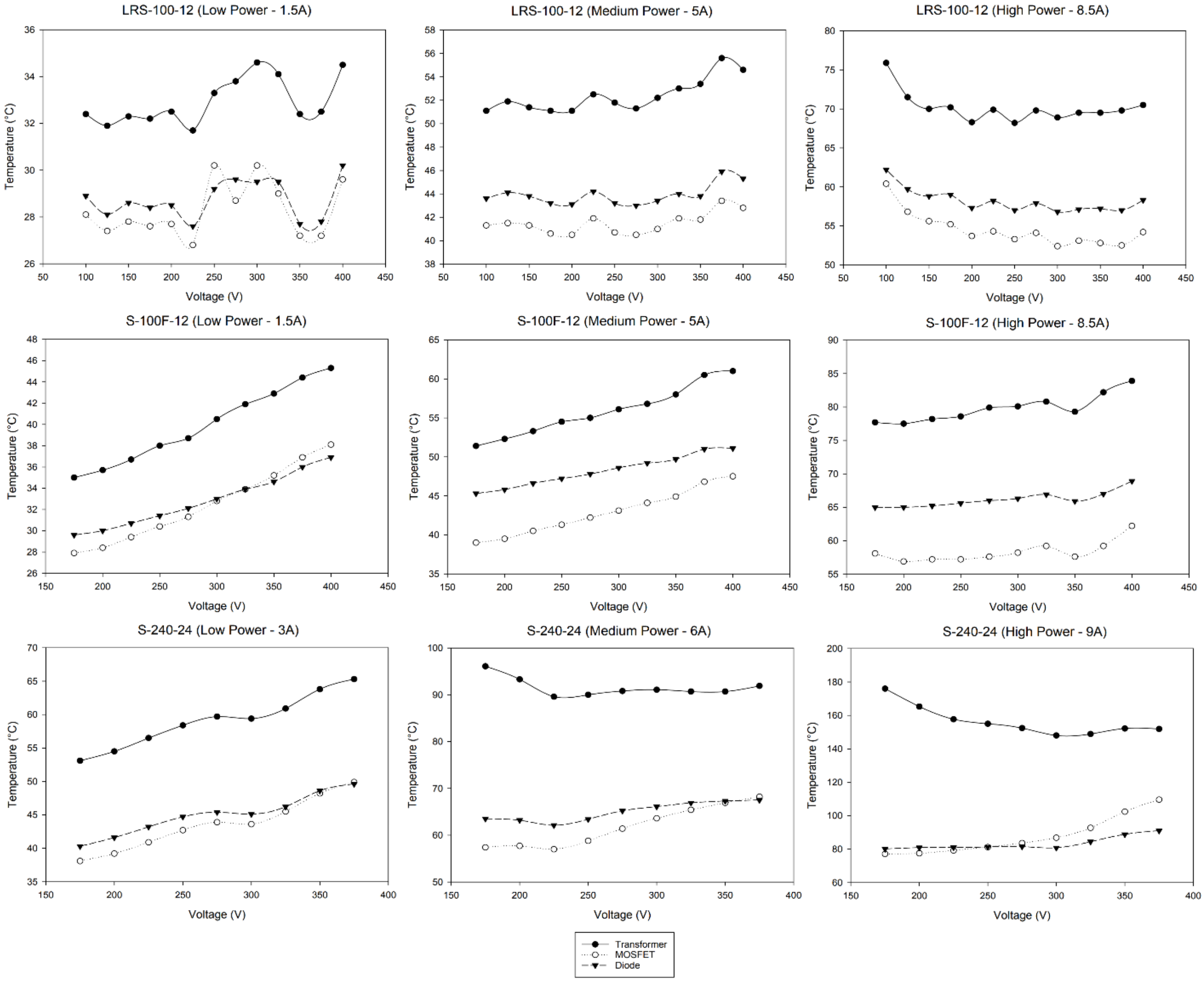

Fig. 7. Thermal characteristics of key components in a select number of HFT power supplies driven with variable DC voltage at select output loads.

4.3 Assessment of an ECM Circuit

A PerfectSpeed 373 W (0.5 horsepower) ECM was chosen as the device to explore variable DC voltage injection simulating direct solar energy powering of an electric motor. Much like the previous power supplies, the bridge rectifier was removed from the circuit board and DC voltage was applied to the positive and negative points as the main power input, however in this case an AC voltage was still required to be present to operate the isolated low power control system of the ECM. Electrification using a variable DC voltage source proved to be successful and the motor was able to be driven by any DC voltage within a window of 225 – 400 V_{DC}. Thermal characteristics of the major ECM components during operation were reserved to measurement of the main IGBT bridge package and the stator coils. The results of the testing proved favourable to the proposal as heat generation remained mostly constant over the entire window of operation as seen in Fig. 8. Interestingly as was observed with HFT circuits, the motor appeared to run cooler as the DC voltage was reduced despite the motor having to draw more current to maintain its set output speed requiring 235±3 W to operate except at 225 V_{DC} where motor speed sag occurred, and 201 W was used. The reduction in component temperatures did not appear to be attributed to change in ambient air temperature over time. Unlike the previous power supplies tested, the response of the system was found to be quite slow, where even a change as low as 10 V_{DC}/s in the input voltage had a significant impact on the motor speed causing it to speed up or slow down depending on an upward or downward change in voltage. After the disturbance in input voltage, the motor was able to recover to its setpoint within a few seconds without issue. It is likely that the response time of the motor can be improved drastically to react much faster, and the observed response time of the motor is a result of unintended operation that was never considered during its design.

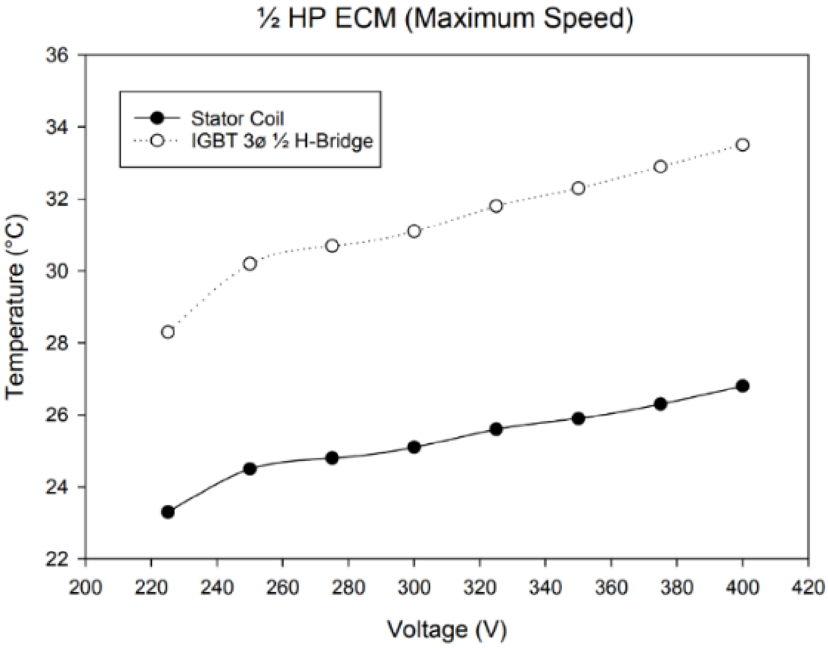

Fig. 8. Thermal characteristics of key components in an ECM driven with variable DC voltage.

4.4 Assessment of Energy Storage Capacity

The assessment of thermal energy storage in the proposed solar enhanced HVAC system is completed using simple heat capacity calculations applied to the contents of the water tanks and avoids further complexities of the HVAC system operation with intention to be used as a rough estimate only. Additional factors such as building size, insulation levels, climate zone, and other variables that determine the final effectiveness of the overall system become too tedious to consider the many possibilities and lie outside the scope of this paper. For the assessment, the water tank capacities will be assumed to be 151 L (40 gallon) each, a common size that can be found sold at a reasonably low price. The potable water tank will be at a minimum temperature of 50 °C before switching from grid to solar energy heating. The non-potable water tank will be assumed to be filled with a 20% ethylene glycol antifreeze solution with a density of 1030 kg/m^3 to avoid the possibility of ice formation inside the heat exchanger. Heat capacity values used will be the average of the upper and lower temperatures encountered inside the tanks based on experimental data [32]. Thermal energy storage capacity of the tanks is compared to new NiCd and Li-ion batteries with average energy densities by mass of 94 kJ/kg and 360 kJ/kg, and average charge efficiencies of 75% and 90% respectively [33].

4.4.1 Air Heating Mode Energy Storage

The available temperature range in tank T1 for energy storage will be from 50 – 90 °C while tank T2 will have a greater range available of 20 – 90°C. Since the electricity will be converted completely to thermal energy the effective energy conversion efficiency will be considered to be 100%.

$$\Delta H_{heating} = \begin{pmatrix} \left(1000\,\frac{kg}{m^3}\right)\left(4.196\,\frac{kJ}{kg°C}\right)(40\text{ °C}) \\ +\left(1030\,\frac{kg}{m^3}\right)\left(3.550\,\frac{kJ}{kg°C}\right)(70\text{ °C}) \end{pmatrix}(0.151\,m^3)$$

$$\Delta H_{heating} = 64000\,kJ$$

The resultant energy storage capability is roughly equivalent to that available from a 908 kg NiCd battery or a 198 kg Li-ion battery.

4.4.2 Air Cooling Mode Energy Storage

The available temperature range in tank T1 for energy storage will be from 50 – 90 °C while tank T2 will have a lesser range of 3 – 20 °C available for chilled water. As before, effective energy conversion efficiency for heat storage will be set to 100%. The refrigeration cycle of the central air system will be given a conservative value for the coefficient of performance of 2.0, in line with values encountered in literature [34]. In the proposed system, the stored chilled water will be able to effectively absorb thermal energy up to room temperature due to the fact that the heat exchanger HE along with variable control of the refrigerant compressor can be used to maintain the chilled water temperature at a set value reaching the AHU regardless of tank T2 temperature.

$$\Delta H_{heating} = \left(1000\frac{kg}{m^3}\right)\left(4.196\frac{kJ}{kg°C}\right)(40\ °C)(0.151\ m^3) = 25300\ kJ$$

$$\Delta H_{cooling} = \frac{\left(1030\frac{kg}{m^3}\right)\left(3.416\frac{kJ}{kg°C}\right)(17\ °C)(0.151\ m^3)}{2.0} = 4500\ kJ$$

The resultant energy storage capability is roughly equivalent to that available from a 423 kg NiCd battery or a 92 kg Li-ion battery.

5. CONCLUSIONS

A proposal for an alternative SSRE solar power system configuration having reduced cost and complexity for household applications has been considered. A combination of hydronic thermal energy storage with a minor rework of electronic appliance power supplies can produce a system that meets the criteria required for a viable solar power system of equivalent utility as current battery-inverter based systems. Specifically, the efficient use of solar panels through MPPT regulation as well as a method of energy storage for buffering and regulating the produced power is achieved. Emphasis is placed on the use of simpler, less expensive, and longer lasting hydronic equipment to fulfill the energy demand of households which are greatly lopsided towards thermal energy needs. Simple calculation of energy storage capacity of standard hot water tanks is found to be of comparable amount as would be found in typical rechargeable battery arrays. The elimination of batteries, especially those containing lithium, as a necessary component of the system is beneficial as the cost and scarcity of lithium may increase substantially as electric vehicle markets intensify. An analysis of the performance of present-day switch mode power supplies shows a wide range of acceptable voltage limits with some circuits capable of operation from as much as 100 to 400 V_{DC} input with no ill effect to the unit through overheating. Such wide tolerance in input voltage and regulation capability already existing in consumer goods should be taken advantage of for its practical usage in SSRE systems especially when modification to a dual mode electrification scheme requires minimal additional expenditure in manufacture. The significant regulation capability of the SMPS found inside an ECM can also provide a solution to air conditioning needs where grid and raw solar power may be used at the same time to energize a variable speed refrigerant compressor when coupled into the hydronic system through a heat exchanger. Such a system could adequately cover most of the major energy requirements of a household where the remainder of electric loads that are either too low powered to be concerned with or too high powered and demanding on an SSRE system can be handled by existing grid power.

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