A power sharing series power BJT array with isolated low voltage control for AC power control applications

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***Abstract*—A technique for a continuously variable AC resistance using a series BJT array is presented. This array provides high power dissipation capability and uniform voltage and power distribution across the individual transistors. The array, controlled using a set of optoisolators to maintain the electrical isolation between the control circuits and the power stage, could be used as the basis to develop several useful techniques including a solid state AC regulator with comparable performance to the commonly used ferro-resonant systems; a linear AC electronic load suitable for testing UPS and other power conditioners; and, in other AC power control applications such as switching capacitors in AC resonant circuits.**

Key words: AC Power Control, AC Regulators, Bipolar Power Transistors, Digital Control, Electronic AC load

I Introduction

Varying the effective impedance of a power transistor to implement a linear regulator or an electronic DC load is a well established technique. However developing a variable AC impedance with fast transient response for operational requirements such as 230V/50 Hz or 120V/60Hz is a challenging task. A continuously variable AC resistance can be easily combined with other control circuitry to develop solid state AC voltage regulators, variable electronic AC loads and in several other applications.

Developing a variable AC impedance with sufficient power handling capability requires several special characteristics such as (i) equal power dissipation and voltage distribution among transistor elements with reasonable device temperatures (ii) fast transient capability and low harmonic distortion on the output waveform (iii) electrical isolation for low voltage control circuitry (iv) simple and easy control. This is particularly the situation when the power handling capacity of the load is in the order of few 100 watts to few kilowatts. In order to achieve the above a large signal circuit design approach need be used, while accommodating the wide variation of the instantaneous voltage over the AC cycle.

First part of the paper describes the generalized theoretical approach, design simplifications and the successful implementation of a power sharing series transistor array with uniform voltage distribution across the elements and electrically isolated control inputs, together with some representative experimental results for a 4 element array. This generalization is based on the successful practical implementation of a solid state AC regulator technique [1-3] based on a series BJT array.

Second part of the paper briefly describes the implementation of a 1kVA output capability solid state AC regulator and the basic approach to develop a linear AC load based on digital control suitable for automatic testing of uninterruptible power supplies (UPS) and other AC to AC converter systems such as power conditioners etc.

II Concept

A conceptual approach for changing the effective collector-emitter resistance of a BJT over a wide range is shown in Figure 1 where a bipolar power transistor (or an array) is inserted between the bridge points of a diode bridge to achieve AC operational capability. When the transistor array is used in 230V AC applications such as in an AC regulator design the instantaneous peak values often vary up to approximately $330\sqrt{2}$ V for a range of input AC RMS voltages from 160V to 260V [5]. Such practical circumstances make the voltage drop of 1.2V across the pair of diodes in the bridge negligible compared to instantaneous voltages. For a simplified case of a single transistor, impedance control can be achieved by diverting a part of the base current using suitable low voltage control circuits. For this situation, referring to Figure 1 when the transistor is in active mode,

$$v(t) = v_{BE} + R_B(i_B + i_x) \qquad (1)$$

where *v(t)* is the instantaneous collector-emitter voltage, v_{BE} is the base-emitter voltage, i_B is the instantaneous base current, i_x is the amount of base current diverted by control inputs and R_B is the resistance between collector and base. With the condition $i_C = \beta i_B$, and using the relationship in Eqn (1) the equivalent effective collector-emitter resistance, R_{CE}, for large signal conditions is,

$$R_{CE} = \frac{v_{BE}}{\beta i_B} + \frac{R_B}{\beta}\left(1 + \frac{i_x}{i_B}\right) \qquad (2)$$

From the Eqn (2), the resistance between the collector and the emitter can be easily controlled by varying R_B or suitably changing the i_x value. Also under practical circumstances the term $\frac{v_{BE}}{\beta i_B}$ can be neglected if R_B is sufficiently large compared to the base emitter resistance. This in effect indicates that we need to control the ratio $\frac{i_x}{i_b}$, which is defined as the base current diversion ratio (BCDR). As the base-emitter voltage is very low compared to the instantaneous line voltages appearing across the power transistor, to control the BCDR, output stage of an optoisolator could be used. This technique in addition provides the necessary electrical isolation between the low voltage control signals and the power stage. In a practical application with Darlington pairs, the effective base emitter voltage will be between 1 to 2 Volts and it practically permits the concept of controlling the BCDR using opto isolators and low voltage control circuits.

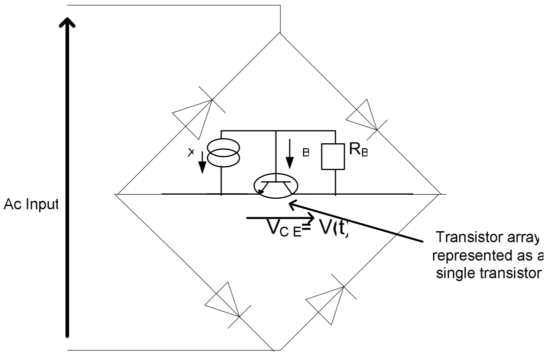


Figure 1: Basic concept of AC impedance control using a BJT and a diode bridge, using base current diversion principle

III Application of the basic concept to multiple transistors in a series connected array

In order to control over a few hundred watts in a situation such as in an AC voltage regulator or in an electronic AC load, the concept in Figure 2(a) can be used. In this configuration of series connected transistors an important criteria is to maintain equal power dissipation and equal voltages across the transistors. In this situation, voltage across the m^th^ transistor, v_{CEm}, is $\frac{v_c(t)}{n}$, where $v_c(t)$ is the instantaneous voltage across the transistor array and *n* is the number of transistors. If all the transistors are to dissipate equal power, the base currents and collector currents need be equal. In this situation,

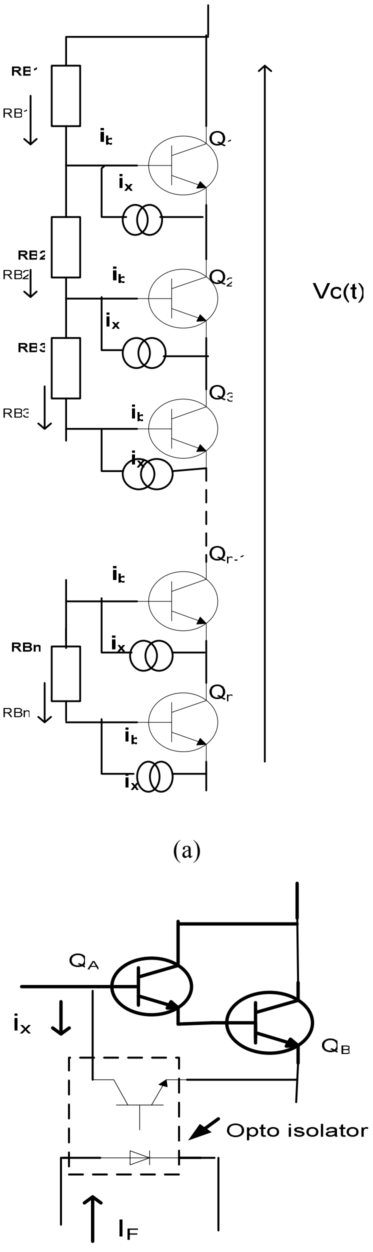
$i_{B1} \approx i_{B2} \approx i_{B3} \approx \ldots\ldots\ldots \approx i_{Bm} \ldots\ldots\ldots\ldots \approx i_{Bn}$

If transistor gains are large and identical, and if each transistor has nearly identical collector currents,

$$i_{RBn} = (i_b + i_x);\; i_{RB(n-1)} = (i_b + i_x)2;$$
$$i_{RB(n-2)} = (i_b + i_x)3; \ldots\ldots\ldots\; i_{RB1} = (i_b + i_x)n \ldots (3)$$

Also,

$$R_{B1}(i_b+i_x)n + R_{B2}(i_b+i_x)(n-1) + R_{B3}(i_b+i_x)(n-2) + \ldots\ldots \pm R_{Bn}(i_b+i_x) = v_c(t) - v_{be}$$
(4)



(a)

(b)

Figure 2: Power sharing transistor array of n elements (a) configuration (b) the Darlington pair driven by an opto-isolator output

where R_{B1} *to* R_{Bn} are the resistors connected between the collector and the base of each transistor and v_{be} is the emitter-base voltage for transistors.

If ,

$$R_{B1} = \frac{R_B}{n}; R_{B2} = \frac{R_B}{(n-1)}; R_{B3} = \frac{R_B}{(n-2)}; .. R_{Bn} = R_B \;\ldots. (5)$$

Eqn (4) reduces to,

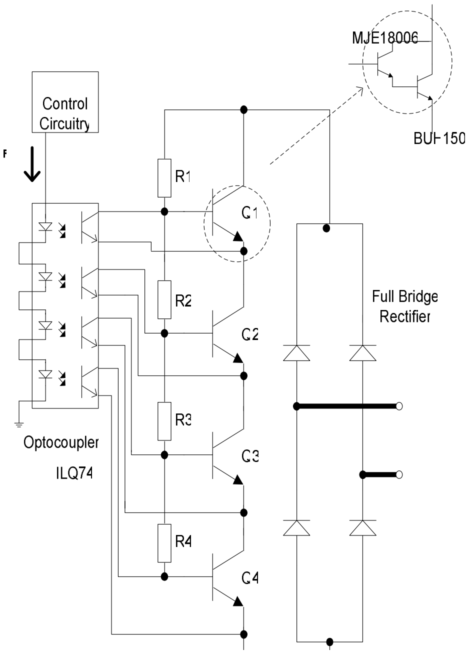
$$v_c(t) - v_{be} = nR_B(i_b + i_x) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Substituting the condition that $i_c = \beta i_b$ in Eqn (6)

$$\frac{v_c(t)}{i_c(t)} = R_{CE} = \frac{nR_B}{\beta}(1+\frac{i_x}{i_b}) + \frac{v_{be}}{\beta i_b} \ldots\ldots\ldots\ldots\ldots(7)$$

Under practical circumstances where v_{be} is generally small compared to $v_c(t)$, Eqn (7) can be approximated as,

$$R_{CE} \approx \frac{nR_B}{\beta} \quad (1+\frac{i_x}{i_b}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(8)$$



$R_1=R_B/4$; $R_2=R_B/3$; $R_3=R_B/2$; $R_4=R_B$

Figure 3: An array of 4 power transistors with an isolated control drive using optoisolators

Figure 3 indicates a case of a four-element transistor array, with a very simple control strategy of series connecting the emitter diodes of a set of 4 identical optoisolators in a single package. This technique simplifies the control circuitry while maintaining the necessary electrical isolation between the power stage and the low voltage control circuits. Impedance control is achieved by controlling the BCDR with fixed R_{Bn} values maintaining the conditions in Eqn (5).

IV Impact of device nonlinearities and the limits of the effective resistance

To analyze the overall effect of the device nonlinearities, basic current transfer relationship, $I_C = K(\frac{I_F}{I_{F'}})^p$, for an optoisolator [6] and the approximate i_b versus V_{BE} relationship for a bipolar transistor [7] can be substituted for i_x and i_b in Eqn(8). When the transistors are in active condition,

$$R_{CE} \approx \frac{nR_B}{\beta} \quad [1+\beta \frac{K(\frac{I_F}{I_{F'}})^p}{I_S e^{\frac{qV_{BE}}{kT}}}] \ldots\ldots\ldots\ldots\ldots\ldots\ldots(9)$$

where, I_F is the DC current through the diodes of the opto isolators, $I_{F'}$, p and K are the device parameters of the optoisolator [6]. k is the Boltzman Constant, T is the absolute temperature and q is the electron charge. I_s is the saturation current for the identical transistors Q_1 to Q_4. In a practical transistor array as per Figure 3 where Darlington pairs are used to achieve easier control with low base currents, in Eqn (9) the term $I_S e^{qV_{BE}/kT}$ is replaced by the equivalent relationship for the Darlington pair [8,9]. If a Darlington pair is to be treated as a single compound transistor for analytical purposes, Fig 4 depicts its overall behaviour with a reasonable mathematical fit for its transfer characteristics representing the equivalent of the term $I_S e^{qV_{BE}/kT}$ in Eqn (7). It is evident from the Figure 4 that the R_{CE} value could be varied when the effective V_{BE} for the Darlington pair is above 1.0 V approximately.

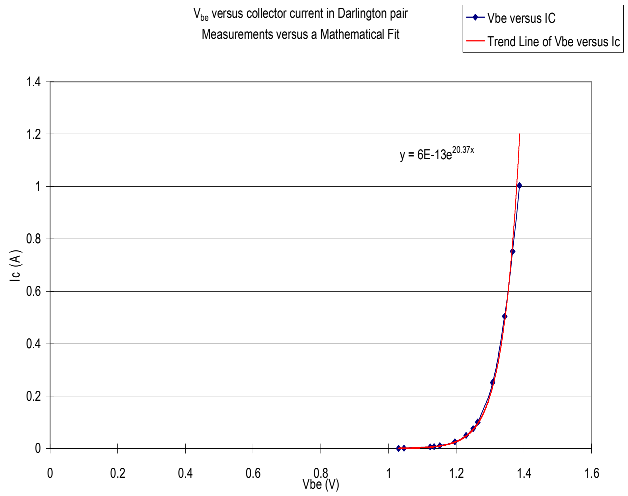


Figure 4: Transfer characteristics of the Darlington pair with an approximate fit for the equivalent single transistor

From figure 4 it is also evident that the Darlington pairs enter into a cutoff condition when the compound V_{BE} value for the Darlington pair is less than about 1.0 Volt. This is the case for the maximum BCDR, where the base current of the transistors are totally removed by the action of the optoisolators. Under this condition, the effective resistance of the array is not controlled by the transistors, except for the leakage effects. If the transistor leakage effects are neglected and the conditions in Eqn (5) is maintained, the effective maximum resistance of the array reaches the value given by the series combination of the resistors R_{B1} to R_{Bn},

$$R_{CE\max} = R_B + \frac{R_B}{2} + \frac{R_B}{3} + \frac{R_B}{4} + \ldots \frac{R_B}{n} \ldots\ldots\ldots(10)$$

At the other extreme, when the current through the input diodes of the optoisolators is zero (the case of minimum BCDR), the effective resistance of the array reduces to $\frac{nR_B}{\beta}$. In between these two limits the overall resistance of the array, R_{CE}, can be controlled by varying the current through the series connected diodes.

From Eqn(10) the maximum value of effective resistance for an array of 4 elements is approximately $2.1R_B$, neglecting the effects of leakage currents in transistors. From Eqn(8) the minimum resistance for the array is approximately $4R_B/\beta$. This clearly indicates a very wide range of ideal performance possible. However due to nonlinear behaviour of the semiconductors, including the dependence of β on the collector current [10], the effective resistance will be a more complex nonlinear function. Reference[11] suggests a methodology for analyzing the nonlinear behaviour of the circuit. However this discussion is beyond the scope of this paper.

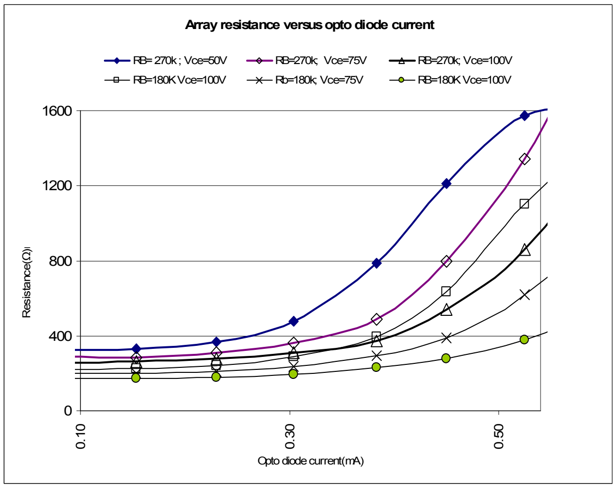


Figure 5: Practical performance of a 4 element transistor array for R_B values of 180kΩ and 270kΩ

V Experimental results

Figure 5 indicates the variation of the effective resistance versus control input I_F for R_B values of 270kΩ and 180 kΩ for a four element array (as in Fig 3) capable of 100W dissipation. It is clear that the lowest value reaches the theoretical value expected from $4R_B/\beta$. As indicated in figure 5 for the case of 50V AC input with R_B=270kΩ, the array reaches a maximum at higher values of I_F as per predictions. However the maximum value is significantly lower than the expected due to leakage effects of the transistors and diodes. [Due to high leakage currents in the power Darlington pair the effective maximum resistance drops].

Also the graphs indicate the dependence of the effective resistance on the AC line voltage, due to device nonlinearities and the dependence of β on the instantaneous collector current over the AC cycle.Another practical situation is that the transistors used in the circuit has non identical β values. In this situation it is easy to compensate by slightly adjusting the R_B values deviating from the relationships in Eqn (5)

VI Application examples

A. Design of an AC regulator based on the technique

Figure 6 indicates the concept and the implementation block diagram of a 230V/50Hz capable 1KVA regulator based on the same principle. This technique was developed [2] to overcome the frequency sensitivity, waveform distortion and the lower overall efficiency of the commonly used ferro-resonant regulators and the slow response of motor driven variacs [4,5]. A comparison of commercial power conditioners and AC regulators is available in Ref 12.

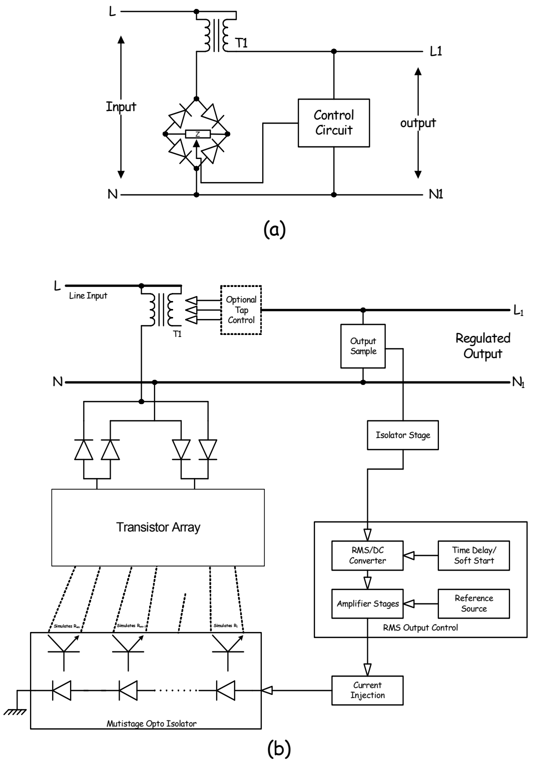


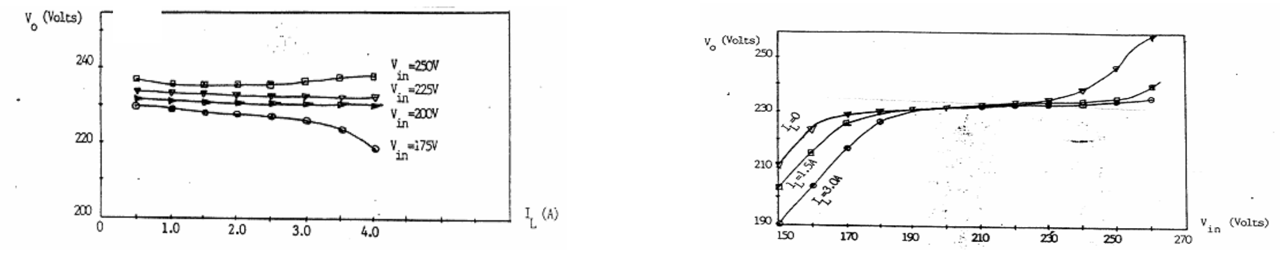
Figure 6: BJT array based Ac regulator (a) basic concept (b) implementation of a 1kVA prototype [2,5]

Figure 6(a) indicates the basic approach to developing a BJT array based AC regulator [1-3]. The transformer T_1 allows the boost or buck operation, based on the input voltage. When the input voltage varies from the lower limit (160V) to the higher limit (260V) the effective resistance of the array varies depending on the load current. This can be indicated by the following relationship,

$$v_{out} = v_{in}(1+\frac{1}{N}) - \frac{R_{array} I_L}{N^2} \quad \text{.........} \ (11)$$

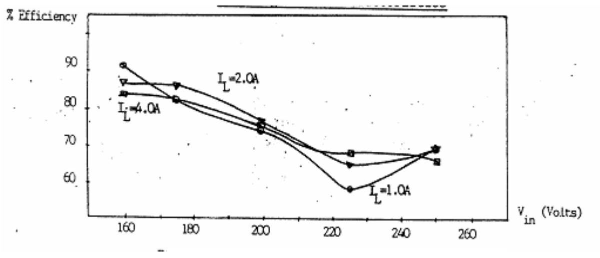
where V_{out} and V_{in} are the output and input AC voltages, I_L is the load current and N is the transformer turns ratio.

Control circuit compares the actual RMS output with a reference value and adjusts the current flowing in the series connected opto isolator input diodes. This effectively controls the value of R_{array} which is the impedance of the series transistor array. Figure 7 indicates the performance of the system in Figure 6(b) based on a four element array built using Darlington pairs of 2N6773 and 2N4923. The technique can be easily enhanced with a digital control subsystem



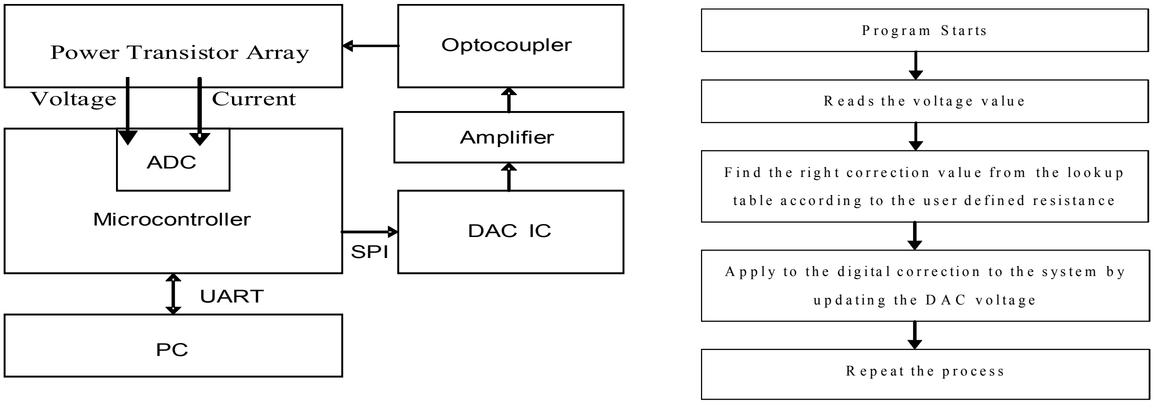
(a)Load Regulation

(b) Line regulation



(c) E fficiency

Figure 7: Performance of a solid state AC Regulator as per design shown in Figure 6(b)
(a) Load regulation (b)Line regulation (c)Efficiency



(a) Block diagram ***(b) Flow Chart***

Figure 8: Simplified approach to digitally controlled AC electronic load using an ATmel Mega8 processor

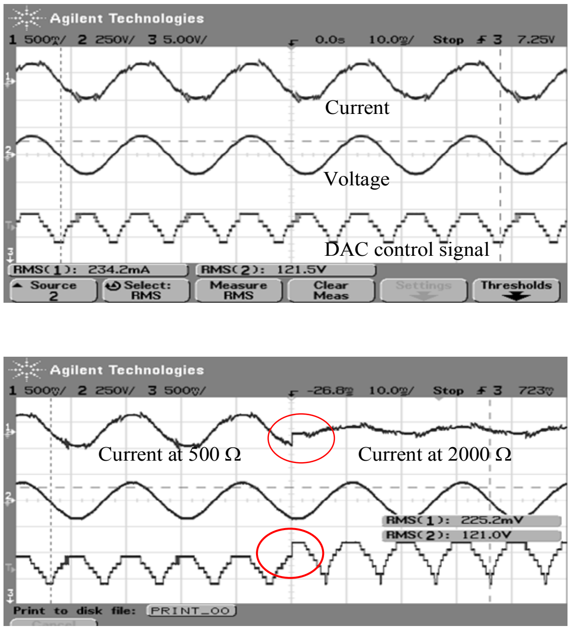


Figure 9: Waveforms in the digitally controlled AC load(a)Voltage and current through the array and DAC control (b) Transient performance

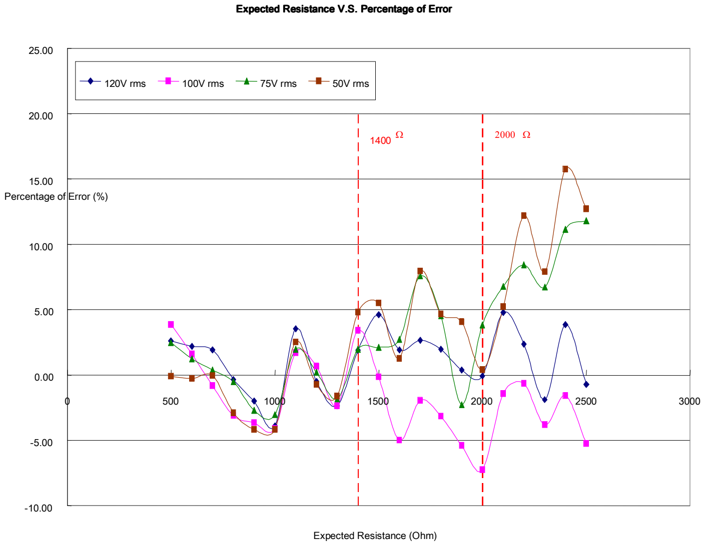


Figure 10: Expected resistance versus percentage error

to meet or exceed the efficiency of bulky ferro-resonant regulators [which could have around 250 to 300 W dissipation per output kVA]. The major design advantage of this technique over the ferro–resonant regulators is the use of a smaller capacity ordinary transformer without any air gap in the core.

B Electronic AC Load

Another useful application of the technique is in an electronic AC load. The design approach for an AC electronic load with processor control is indicated in Figure 9. Figure 8(a) indicates the use of an ATmel 8 bit processor coupled with the array where the current and the voltage of the transistor array is fed into the ADC for setting the resistance. Figure 8(b) indicates the software flow chart.

The electronic AC load (currently under development) allows us to compensate for the nonlinear behaviour of the array using a digital correction algorithm. The system takes care of the non linear behavior of the array due to the dependence of the transistor parameters on the instantaneous voltages of the AC cycle.

Figure 9(a) indicates the voltage and current through the load and the control output of the D to A Converter (DAC) used. Figure 9(b) indicates the transient behavior of the array and the associated DAC output with the program set to switch the resistance between 500Ω and 2000Ω. Figure 10 indicates expected resistance as per loaded program and the actual percentage error achieved, without optimizing the system. To further reduce the percentage error in Figure 10 system need to be tuned and the work is in progress.

VII Conclusion

The concept of using a series transistor array with opto isolator based control can be used in several AC power control applications such as AC voltage regulators, AC electronic loads, and miscellaneous other applications such as switching of AC resonant circuits etc. Further investigations are in progress in relation to improving the linearity and the control aspects. With the availability of IGBT modules, by suitable design modifications, the concept can be applied to much higher power requirements in electronic AC loads etc.

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