Design of Programmable Inductive Voltage Divider using Minimum Inductive Elements

A. Eliwa Gad, M. Helmy A. Raouf, A. A. Ammar

Abstract: ***In this paper, a proposed inductive voltage divider is described to be operated manually and automatically, which is not provided by the ordinary decade inductive voltage dividers. Design of that programmable inductive voltage divider (PIVD) is investigated and presented in detail. The introduced PIVD mainly consists of inductive elements, relays, microcontroller to get the required output voltage ratios through its three stages. This PIVD is designed to produce 999 steps in the range from 1×10^{-3} to 999×10^{-3} output ratios using minimum inductive elements and reed relays. Simulation of this PIVD has been performed and illustrated as well as practical design components are discussed in detail.***

Keywords: ***Programmable inductive voltage divider; Reed relays; simulation; Microcontroller; voltage ratio***

I. INTRODUCTION

AC voltage ratios can be obtained using different techniques such as resistive, capacitive and inductive voltage dividers (IVD_s). Ideally inductive and capacitive dividers do not dissipate any power, but practically they dissipate some power because they have some internal parasitic resistance. On the other hand, resistive voltage dividers consume the energy in terms of heat. These dividers are not suitable to operate at high frequencies because the parasitic elements are significant so the voltage division may be vastly different[1]. Particularly for accurate electro-magnetic measurements, IVD_s are recommended due their high input impedance, low output impedance, high accuracy and better stability[2]. Generally, IVD_s are widely known as the precise ratio reference with better stability and used to provide ac voltage and power standards[3]. One of the IVD applications is the evaluation of a transformer ratio of a bridge used for accurate impedance measurement[4], [5]. In addition, a precise IVD is an important component of sinusoidal and non-sinusoidal power measurement systems[6]. Configuration of a conventional decade inductive voltage divider (DIVD) is shown in Fig. 1. Generally, each stage of such inductive voltage divider generates 10 voltage ratios using 11 inductive elements [7]. There is a mutual inductance between coils of these inductive elements so, it is not ideal inductive divider [8]. This leads to increase electromagnetic interference, residual capacitive and resistive values between its inductive elements[9]. In addition, effect of the accumulation error reduces the accuracy of output voltage[10]. In such old dividers, each stage is controlled manually using a dial switches as shown in Fig.1, therefore variable contact resistance in such switches often greatly affects the stability of the voltage ratio measurements. Also, the conventional DIVD cannot be used in automated measurement systems or checking the linearity of their devices [11].

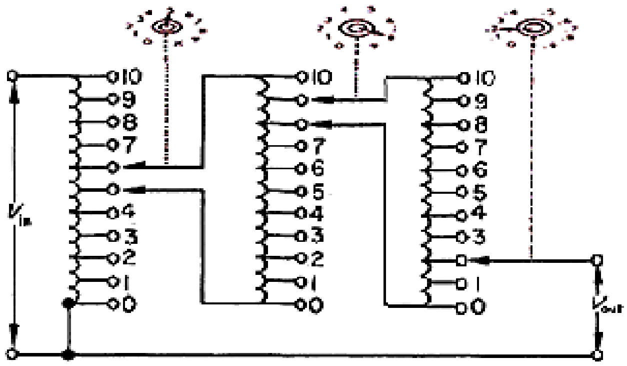

Fig.1: Conventional manual inductive voltage divider with 0.582 selected ratio.

To solve the problems of the traditional DIVD, a programmable inductive voltage divider has been introduced in this paper. The demonstrated PIVD has three stages and each produces 10 different ratios. First and second stages have the same design and each has six inductive elements, whereas the last stage has only five inductive elements. Main idea of the proposed PIVD design is using minimum inductive elements to obtain the required output voltage ratios with different control methods, which is innovative work. The PIVD can be controlled manually or automatically to be used in different automation applications. This PIVD is controlled by using a group of reed relays through a microcontroller to produce 999 output ratios. The microcontroller drives the reed relays through a specially prepared C-program. The PIVD design has been simulated and validated by using Proteus program as explained and presented in detail.

II. DESIGN AND STRUCTURE OF THE PROPOSED PIVD

Design of the PIVD is mainly based on four parts; inductive elements, reed relays, microcontroller and output ratios. Firstly, the idea of reducing the number of inductive elements is important to improve the performance of this PIVD as will be clearly explained during the last section of this paper. As demonstrated in Fig. 2, the PIVD has been designed by three stages.

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First and second stages have six inductive elements for each, while the last stage has only five inductive elements. This divider is designed to achieve high input impedance and low output impedance due to its special design. So, the inductive elements values of the proceeding stage depend on the values of inductive elements of the preceding stage by dividing its values by 5. For example, the first stage has nominal inductive values of L_1=L_2=L_3= L, L_4=L_5 = 2L and L_6= 4L, also the nominal inductive values of the second stage are L_7=L_8=L_9= L/5, L_{10}=L_{11} = 2L/5 and L_{12}= 4L/5, but the nominal inductive values of the last stage are L_{13}=L_{14}= L/25, L_{15}=L_{16}= 2L/25 and L_{17}= 4L/25 .

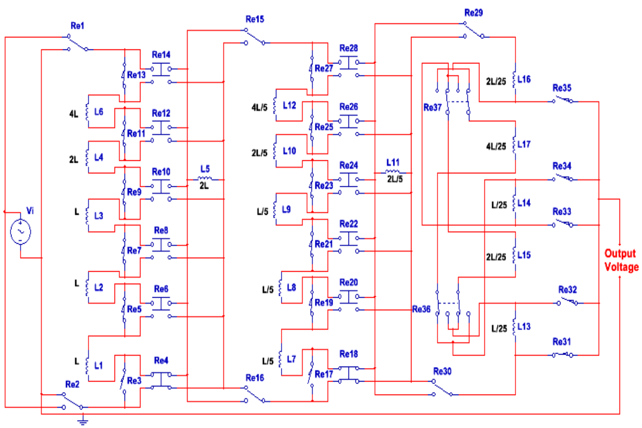

Fig.2: Schematic diagram of the PIVD.

The number of the PIVD output ratios depend on the number of stages which produce 10^S output voltage ratios, where S is the number of stages. The input voltage of proceeding stage depends on voltage across only one inductive element. For example, input voltage of the second stage equal to the voltage across L_5 as demonstrated in Fig.2, where V_{L5} is equal to $0.1V_{in}$. This voltage can be represented by the following equation:

$$V_{L5} = V_{L7} + V_{L8} + V_{L9} + V_{L10} + V_{L11} + V_{L12} \quad (1)$$

A group of reed relays produce output ratios through a microcontroller that has been programmed by a special C-program. Each output ratio depends on voltage across one or more inductive elements. The first stage output ratios can be determined using the following equations:

$$Ratio\ (0.1) = \frac{V_{L1}}{V_{in}} \quad (2)$$

$$Ratio\ (0.2) = \frac{V_{L1}+V_{L2}}{V_{in}} \quad (3)$$

$$Ratio\ (0.3) = \frac{V_{L1}+V_{L2}+V_{L3}}{V_{in}} \quad (4)$$

$$Ratio\ (0.4) = \frac{V_{L6}}{V_{in}} \quad (5)$$

$$Ratio\ (0.5) = \frac{V_{L1}+V_{L2}+V_{L3}+V_{L4}}{V_{in}} \quad (6)$$

$$Ratio\ (0.6) = \frac{V_{L4}+V_{L6}}{V_{in}} \quad (7)$$

$$Ratio\ (0.7) = \frac{V_{L3}+V_{L4}+V_{L6}}{V_{in}} \quad (8)$$

$$Ratio\ (0.8) = \frac{V_{L2}+V_{L3}+V_{L4}+V_{L6}}{V_{in}} \quad (9)$$

$$Ratio\ (0.9) = \frac{V_{L1}+V_{L2}+V_{L3}+V_{L4}+V_{L6}}{V_{in}} \quad (10)$$

Similarly, for other stages; their output ratios can be obtained by the same equations using the schematic diagram illustrated in Fig.2.

III. SETTING OF THE PIVD RELAYS

The inductive elements are connected in series through different groups of reed relays. The first stage has the same number of relays as the second stage, whereas the third stage has a relatively smaller number of relays. This last stage is designed to produce the final output of the required divided voltage. Figure 3 shows relays states of the first stage which are selected to produce the nominal ratios from $1×10^{-1}$ to $9×10^{-1}$ in addition to the ratio of one where the whole input voltage, of a voltage source, is transferred to the divider output terminals.

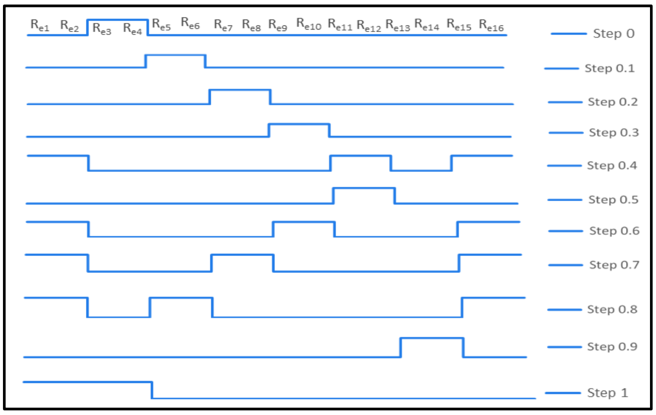

Fig. 3: Relays states of the first stage.

The first stage is connected to the second stage through two relays, R_{e15} and R_{e16}, as shown in Fig.2. The nominal ratios from $1×10^{-2}$ to $9×10^{-2}$ are obtained by setting the relays of the second stage as depicted in Fig.4. In these two stages, the steps values of 4,6,7 and 8 are obtained by using six relays for each step, but only two relays are used to produce each value of the remaining steps as demonstrated in Figs. 3 and 4.

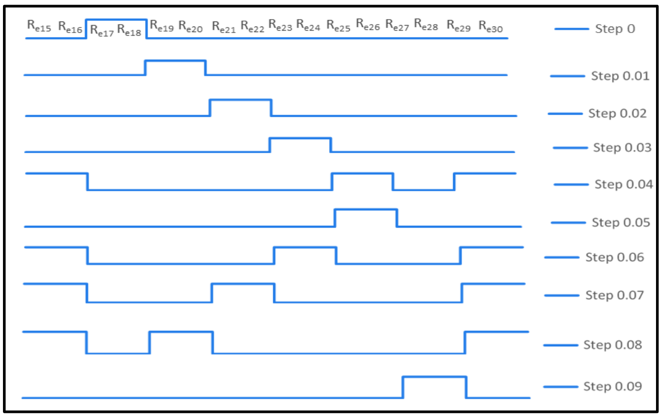

Fig. 4: Relays states of the second stage.

The third stage has a relatively smaller number of relays with respect to the other stages. This stage is designed with different construction where the final divided voltage is obtained at the divider output terminals. Furthermore, it has different settings of relays to obtain the output ratios from $1×10^{-3}$ to $9×10^{-3}$ as illustrated in Fig.5.

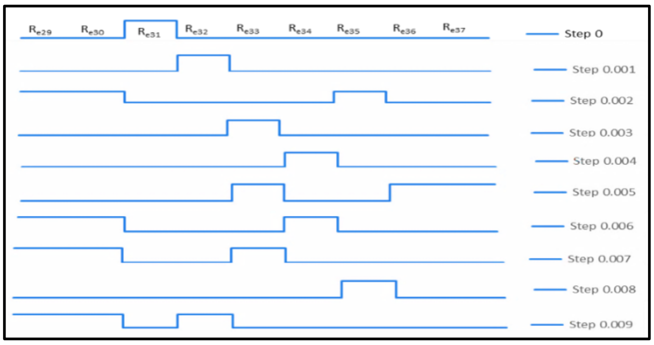

Fig. 5: Relays states of the third stage.

In this stage the 0, 0.001, 0.003, 0.004, 0.008 ratios values are obtained by using only one relay for each step, but the other ratios values are produced by using three relays for each step. Accordingly, each stage produces nine output ratios, but totally 999 output ratios could be obtained by using all possible combinations of the three stages.

IV. SIMULATION OF THE PIVD WITH ITS MEASUREMENT SYSTEM

The new design of the PIVD is fully simulated using the Proetus program. This simulation is mainly based on some modules; voltage source, inductive elements, reed relays, microcontroller, keypad, LCD and measuring device as clearly defined through the block diagram demonstrated in Fig. 6. For automatic control; a computer is connected to the PIVD. Fig. 7 shows user interface of the PIVD simulation which is designed with 37 relays to control the three stages to obtain zero ratio in addition to nine voltage ratios from each stage. They have four contact forms, SPST, SPDT, DPDT, DPST, that are controlled by using one microcontroller. All of the 999 ratios are produced by the maximum different combinations of the three PIVD stages.

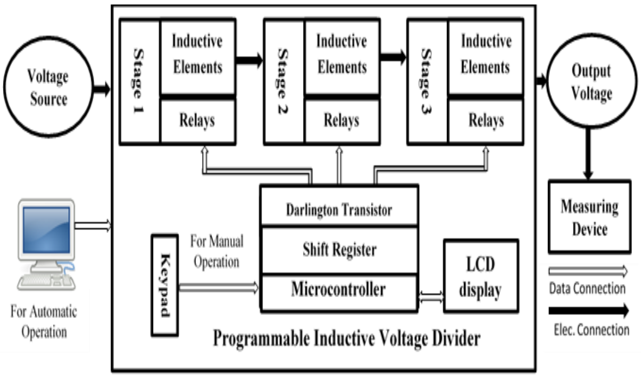

Fig.6: Block diagram of the PIVD and related devices.

The three stages that have 17 inductive elements are used to design the PIVD. For the first stage; the inductive elements are three 100 mH, two 200 mH and only one 400 mH. As well as, the second stage has inductive elements values which are three 20 mH, two 40 mH and only one 80 mH. But inductive elements values of the output stage are two 4 mH, two 8 mH and only one 16 mH. The inductive elements of each stage are connected in series by using the reed relays. While the input of each stage is connected in parallel to one of the inductive elements of the previous stage as shown in Figs. 2 and 7. The microcontroller, ATMEGA8515, could be programmed through a prepared C language program which has been used to control the reed relays to generate the required voltage ratios manually or automatically. Manual control could be obtained using the PIVD keypad. Automatic control will be obtained using a special computer program via Serial-USB cable to derive the microcontroller and generate the output ratios automatically. Then a voltmeter will be connected to the PIVD output terminals to measure the divided voltage as depicted in Fig.6. Therefore, this PIVD has more facilities to be used in automated measurement systems and other useful applications.

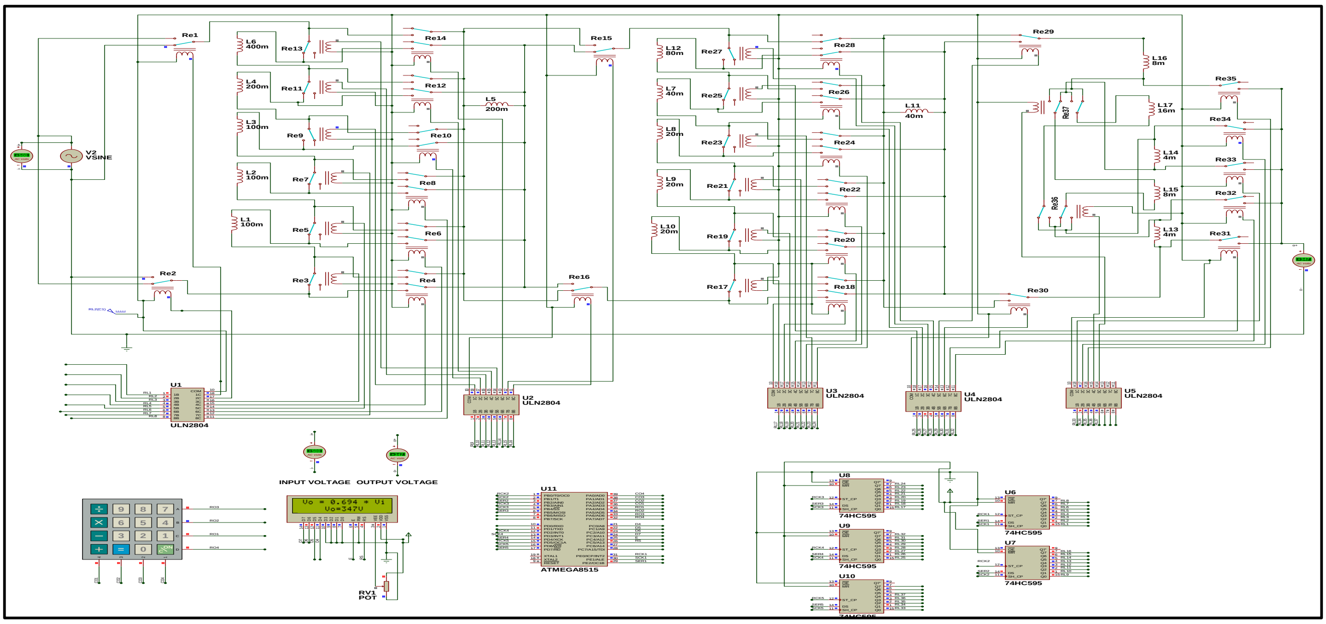

Fig.7: Graphical user interface of the PIVD simulation.

Performance of the reed relays and all components of the PIVD could be verified by comparing input and output voltages with the required dividing ratio. Fig. 8 shows an example to obtain the output ratio of 0.694. Using the PIVD keypad; the input voltage of 500 V is entered and then the required ratio 0.694 is entered. Accordingly, the output voltage is generated with the value of 347 V as clearly illustrated in Fig. 8. In this example, the relays no. 1,2,9,10,15 and 16 are set in active position to get 0.6 ratio, the relays no. 27 and 28 are set in active position to get 0.09 ratio and also relay no. 34 is in active position to get 0.004 ratio. The relays states of this numerical example are illustrated in Fig. 7.

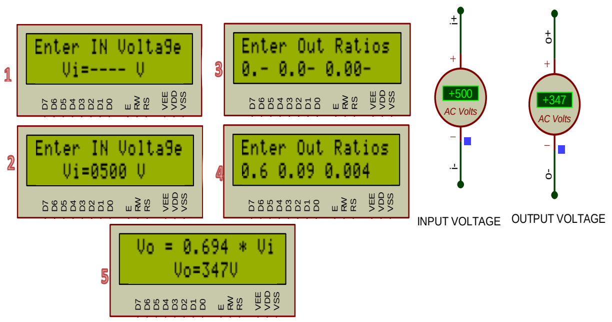

Fig.8: Example for generating 0.694 output voltage ratio using the simulation system.

V. ADVANTAGES OF THE PIVD OVER DIVD

Design of the proposed PIVD has many advantages over the conventional design of the traditional DIVD. The transfer ratio error according to the International Electrotechnical Commission (IEC) 60618[12] can be expressed as in the following equation:

$$e = \frac{V_{on}}{V_{in}} - \frac{V_{oa}}{V_{ia}} \qquad (11)$$

Where e denotes the transfer ratio error, V_{in} ,V_{ia} are nominal and actual input voltage values of each stage respectively and V_{on} , V_{oa} are nominal and actual output voltage values of each stage respectively. In traditional DIVD, transfer ratios errors will be increased when using the combination between stages because the input voltage of the proceeding stage depends on the voltages across different inductive elements. Contrary in the introduced PIVD, the input voltage of each stage is constant while obtaining all of its possible combinations because the input voltage depends on only one constant voltage of inductive element from the previous stage. So, this inductive element can be replaced, if required, to improve the transfer ratio error which depends on the input voltage of each stage as predicted from Eq. 11. This means that the input voltage of the second and third stages are controlled using only one inductive element for each. For example, the input voltage of the second stage is always equal to the voltage across the inductive element L_5 as shown in Fig. 2. So, standard inductive elements with high accuracy should be used when the PIVD is manufactured to improve its performance by reducing the transfer ratio error. In addition, due to the constant input voltage of each stage, the divided ratio results will be near to the ideal nominal case because the accumulated errors will be minimized. The PIVD consists of only one-half inductive elements of the conventional DIVD to achieve the same resolution and obtaining the same number of the output ratios using minimum inductive elements. Therefore, it is more economical to use the introduced PIVD due to its minimum number of the used inductive elements. Accordingly, the electromagnetic interference, parasitic elements and mutual inductance between its inductive elements will be obviously decreased. Therefore, PIVD performance and accuracy will be improved. Traditional DIVD is used in manual measurements through its dial switches which confuses the user when selecting the required ratio. In addition, the switches affect the voltage ratios stability. Whereas the introduced PIVD can be controlled manually or automatically by using the relays system and the microcontroller. So, it can be easily used in the automated measurement systems that have higher precision, stability with minimum effort and time. The disadvantage of the PIVD is that all relays are connected in series through a single path, which increases the effective resistance. To minimize this influence, the relays will be selected to have minimum contact resistance during the manufacturing process of this PIVD.

VI. CONCLUSION

The introduced PIVD has been designed with three stages using 17 inductors and 37 reed relays. It is controlled by only one microcontroller to obtain 10 output ratios per stage. Then, 999 output voltage ratios can be produced by using all possible combinations in the range from 1×10^{-3} to 999×10^{-3}. The necessary equations have been introduced to demonstrate the performance of the presented PIVD. The new design technique allows the PIVD to be used in the automatic measurement systems and then obtaining their beneficial advantages. This PIVD design has many advantages over the DIVD as decreasing the transfer ratio error and using minimum inductive elements. The PIVD design has been completely validated using the full presented simulation system. The proposed simulated PIVD will be practically fabricated, automatically controlled and reliably used in a fully automated measuring system as will be presented in a future work.

REFERENCES

1. Grubmüller, B. Schweighofer, and H. Wegleiter, “Characterization of a Resistive Voltage Divider Design for Wideband Power Measurements”, IEEE SENSORS, pp. 1332–1335, Nov. 2014.
2. W. Wang, Y. Yang, L. Huang, and Z. Zhang, “Establishing of a 1000 V Multi-Decade Inductive Voltage Divider Standard at NIM”, IEEE Access, vol. 6, pp. 58594–58599, 2018.
3. K. Suzuki, “A New Self-Calibration Method for a Decade Inductive Voltage Divider by Using Bifilar Windings as an Essential Standard at Wide Frequency”, IEEE Transactions on Instrumentation and Measurement, vol. 58, no. 4, pp. 985–992, Apr. 2009.
4. S. Kon and T. Yamada, “Load Characteristics of Two-staged Inductive Voltage Dividers”, 29th Conference on Precision Electromagnetic Measurements (CPEM 2014), pp. 758–759, Aug. 2014.

5. B. C. Waltrip, A. D. Koffman, and S. Avramov-Zamurovic, "The Design and Self-Calibration of Inductive Voltage Dividers for an Automated Impedance Scaling Bridge", Conference Proceedings IMTC, vol. 2, pp. 1191–1195, May 2002.
6. T. Yamada, S. Kon, and N. Sakamoto, "Evaluations of a Wideband Inductive Voltage Divider and Non-sinusoidal Power Measurement System", Conference on Precision Electromagnetic Measurements (CPEM 2010), Daejeon, Korea (South), pp. 239–240, Jun. 2010.
7. V. L. Kim, V. N. Dainakov, and A. B. lljin, "Extending of the Frequency Range of a Multidecade Inductive Voltage Divider", 8th Russian-Korean International Symposium on Science and Technology, KORUS, Tomsk, Russia, vol. 1, pp. 241–244, 2004.
8. D. Filipović-Grčić, B. Filipović-Grčić, and K. Capuder, "Modeling of Three-phase Autotransformer for Short-circuit Studies", International Journal of Electrical Power & Energy Systems, vol. 56, pp. 228–234, Mar. 2014.
9. A. Dutta and S. S. Ang, "Effects of Parasitic Parameters on Electromagnetic interference of power electronic modules", IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 2706–2710, Mar. 2017.
10. J. Zhang et al., "Design and Self-calibration of Cascaded Inductive Voltage Divider with Ratio of 2n:1", Conference on Precision Electromagnetic Measurements (CPEM 2016), pp. 1–2, Jul. 2016.
11. M. Helmy A. Raouf, A. Eliwa Gad, El-Sayed Soliman A. Said, and M. A. Elwany, "Fully Automated Inductance Measuring System Using New Fabricated Inductance Box", MAPAN-Journal of Metrology Society of India, vol. 32, no. 3, pp. 199–205, Sep. 2017.
12. "IEC 60618:1978/AMD2:1997- Inductive Voltage Dividers | IEC Webstore." https://webstore.iec.ch/publication/2725 (accessed Apr. 11, 2019).

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