A low-voltage three-phase AC generator built from analogue blocks

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Abstract: - A circuit capable of delivering three 40V_{pp} 50Hz AC voltage outputs with 120º phase separation between them has been built. It uses standard, low-cost electronic components and, unlike other previous similar power supplies [1-3], the present circuit is entirely based on analogue electronics. This power supply was purposely built for educational purposes, where low-voltage is necessary in order to prevent students from suffering electrical shocks. Its design, simple and robust, makes this circuit be an interesting project for undergraduate students, either as part of a regular electronics laboratory course or as a final degree project in electronic and electrical engineering.

Key-Words: DC- to -3-phase AC converters; Negative feedback; Phase-shift oscillator; Output stages.

1 Introduction

The lack of equipments which can be safely used in demonstrating the operation of three-phase systems without the risk of electric hazards poses a serious limitation to first courses of electrical and electronics engineering and science degrees. Consequently, instructors are normally forced to teach these subjects by resorting to theoretical demonstrations, animated graphs and, sometimes, computer simulations. But the absence of laboratory experiments leads students to have a rather poor understanding of electrical and electromechanical devices behaviour. At best, these types of laboratory experiments are carried out under a strict supervision and a carefully controlled situation, so that students do not actually conduct the experiment by themselves.

In an attempt to overcome this problem, various electronic circuits have been proposed [1-4]. Among them, that of Shirvasar et al. [1] uses a microcontroller to generate three signals with a 120 degree phase-separation. The voltage signal is obtained using the PWM technique and the output stage was implemented with six power MOSFET transistors mounted on an H-bridge configuration. The PWM pulses acting on the MOSFET gates are properly furnished by a 16F686 microcontroller.

After assessing the usefulness of such an idea and considering that similar low-cost commercial equipment was not available, we built the circuit described in Ref.[1] and several difficulties appeared. In the first place, the signals were slightly distorted, perhaps, due to the poor sampling and gate-driving signal of the MOSFET and, secondly, the quality of the output AC voltage appeared to depend on the load.

It turned out then, that one can replace the microprocessor-driven PWM system for an analogue oscillator and the H-bridge by three, conventional power amplifier. With this in mind, we devised a three-stage 120 degree phase-shift oscillator followed by three output stages, containing three BJT or MOSFET push-pull followers preceded by three linear preamplifiers.

2 Problem Formulation

Figure1 shows the block diagram of the proposed analogue circuit. It comprises an op amp based phase-shift oscillator capable to generate three 250 mV_p and 50 Hz sinusoidal signals with a phase separation of 120º.

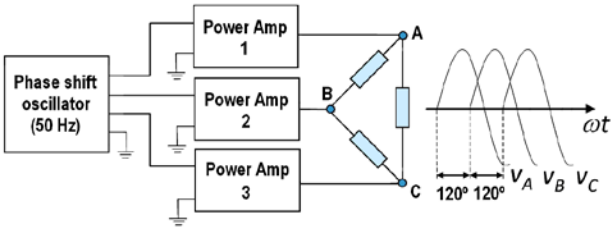

Fig. 1 Block diagram of the DC/3P-AC generator circuit. A three-phase oscillator delivers three, 120º phase-shifted sinusoidal signals, to three independent power stages.

As depicted in the same figure the circuit is feeding three loads connected in the delta configuration, though loads can also be connected in the star configuration. The system is also intended to develop three amplitude stabilized signals v_A, v_B and v_C even when connecting low-impedance loads. As a consequence, one thus needs employing three power output-stages.

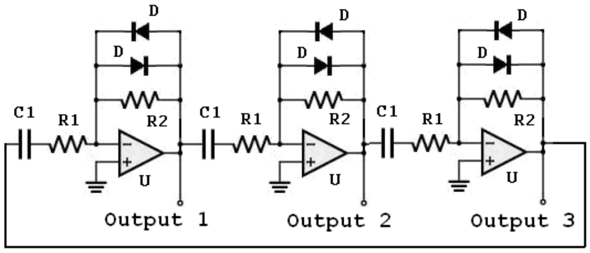

Fig. 2 Block diagram of the phase shift oscillator, where C=100nF, R1=22k, R2=47k, D=1N4148 and U=LF411.

The schematic of the phase-shift oscillator circuit used in this project is shown in figure 2. Three inverters amplifiers, with a closed-loop gain slightly greater than unity and a phase shift of 2π/3, connected in a ring configuration produce the sinusoidal signal, which will be further amplified by the power stages. Observe that the feedback loops of each amplifier contain two diodes connected in parallel but in opposite directions. They form the so-called clipping circuit, necessary to prevent the oscillation amplitude from becoming large and distorted.

It must be noted that the *resonance* frequency of the circuit above is given by the expression $f=\sqrt{3}/(2\pi C1R1)$, therefore, replacing the values in the circuit of figure 2 we obtain f = 42 Hz. Slightly below 50 Hz, but quite acceptable for an early version of this 3P-generator.

2.1 The basic configuration

Considering that negative feedback helps to stabilize amplifiers gain [5], we explored first the circuit shown in figure 3. This configuration, an inverting voltage amplifier connected to a class B power stage, both inside a negative feedback loop, is commonly introduced in textbooks that cover the basic analogue building blocks [6-8]. Although a power op amp can accomplish the same task, as a first attempt we decided to build a more affordable circuit employing low-power op amps and power BJTs as the one in figure 3.

As is well-known, class B amplifiers -like those built in the push-pull configuration- exhibit a greater efficiency than class A ones. Consequently, the former are often preferred as output stages in audio amplifiers. Besides, transistors operate as emitter (or source) followers, boosting the current provided by the op amp.

The output signals of class B output stages, however, are affected by the so-called crossover distortion. This is an intrinsic effect in transistors when driving them from cutoff to active operation mode. In spite of this, a nearly pure sinusoidal signal can be obtained by introducing negative feedback around the open loop amplifier. The open-loop amplifier consists in an op amp driving the push-pull output stage, which does not introduce phase shift since transistors are connected as emitter (or source) followers. Therefore, there is no phase shift between the input voltages of the op amp, as that expected for amplifiers with negative feedback. In this fashion, provided that an ideal op amp has an infinite differential gain, the condition of a virtual short-circuit between the op amp inputs is fulfilled. This fact, together with the assumption of negligible op amp input currents, ensures that the overall gain is mainly determined by the feedback resistors as $1+R_f/R_i$, a result that is highlighted in the aforementioned textbooks.

If v_i represents one of the sinusoidal signals generated by the oscillator, the voltage output developed across the resistive or reactive load should be $v_o = (1+R_f/R_i)v_i$, which is a pure sinusoidal waveform too.

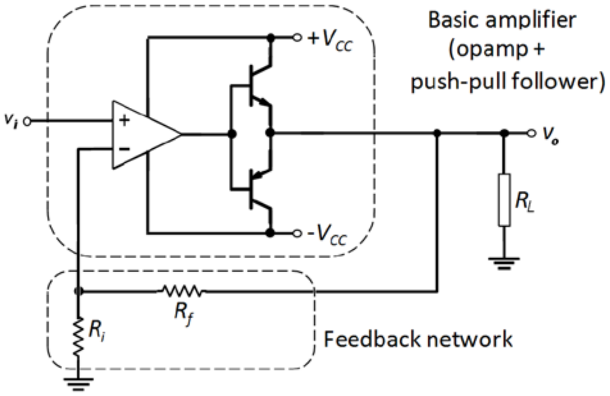

Fig. 3 Basic configuration of the power amplifier block: a non-inverting voltage amplifier with current-boosting capability and a voltage gain which is determined by R_i and R_f.

2.2 Operation with resistive loads

In our first attempt, the circuit operated with voltage supplies of ±18V. Each power amp was built employing an LF411 IC and a pair of complementary transistors (BD437/438). Three resistances rated at 100 Ω/5W were connected to each power stage in the star configuration. For 250 mV_p oscillator voltage outputs, R_i and R_f were picked to obtain about 12 V_p at the output of each power stage. The three signals exhibited the same amplitude, as can be expected when loads are balanced.

2.3 Operation with RL loads

The second attempt consisted in feeding a three-phase motor as indicated in figure 3, where each phase exhibits an equivalent impedance of, approximately, $(36 + j180)\ \Omega$ at 50Hz. The same voltage levels were obtained in this case, and the circuit was capable to maintain the motor running. However, it is observed that, at switching off the power supplies, the complementary BJTs burn out too often. We attributed this effect to the transient overvoltage produced by the coils when the current switches-off, thus driving the operating point of the BJTs outside the safe operating area (SOA).

2.3 Increasing the output signals amplitude

Another drawback of the circuit in figure 3 comes from the maximum voltage swing of the op amp, which limits the amplitude of the output voltage. In an attempt at solving such a difficulty, a suspended supply scheme as proposed in reference [7] was built. The circuit, which is not shown here, worked fairly well with BJT output stages and resistive loads, however, the difficulties that appeared with RL loads remained without being solved.

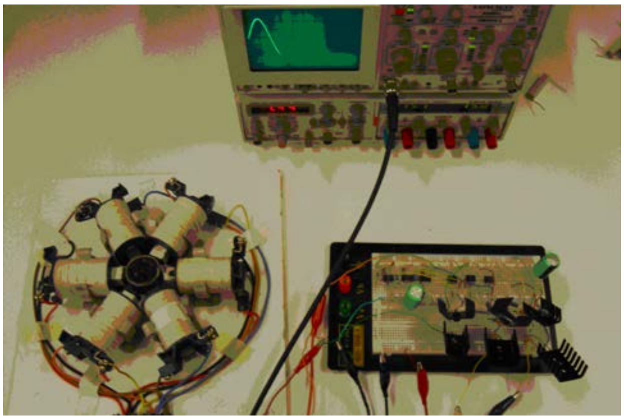

Fig. 3 Picture of the three-phase DC-AC circuit supplying a 3P-inductor motor used in classroom demonstrations.

3 Problem Solution

Such a difficulty, however, appears to be solved by replacing the BJTs in the class B output stage with three power MOSFETs (figure 4). These transistors can be operated with supply voltages up to ±30V. Although low-power high-voltage op amps seem more suitable for this purpose, we did not employ them because they are more expensive. Besides, we had some units of the LM675 power op amps and we decided to employ them to drive each MOSFET push-pull stage.

The circuit worked properly in successive trials and MOSFETs were not damaged after switching off power supplies. We also noticed that, when connecting highly reactive loads, the currents drawn from the supplies did not reach stable values due to thermal drift. This relates to the fact that, at same impedance, reactive loads cause lager power dissipation over the transistors compared to resistive ones. This stems from the phase shift between current and voltage, which gives place to the possibility that the transistor remains "on" for some time, after the output voltage has been reversed. This problem does not seem to be amenable of being solved in a simple way, however, the instability caused by the overheating of the transistors can be kept under control by adding two resistors on the sources of the output MOSFETs, as shown in figure 4.

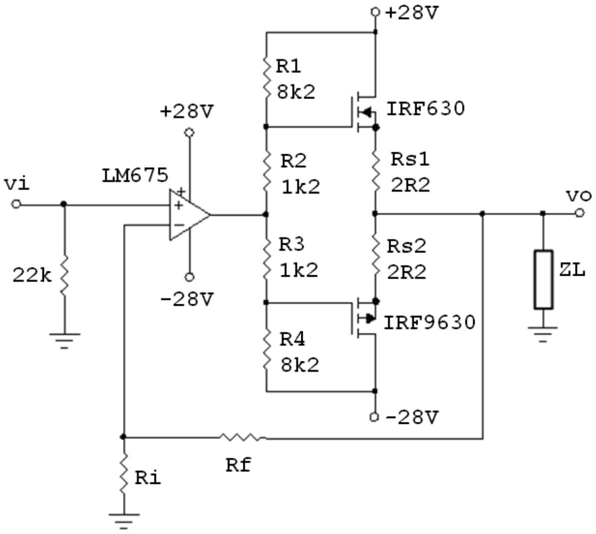

Fig. 4 Power amplifier schematic: MOSFETs are used in the push-pull stage, which is driven by a LM675 op amp.

In order to characterize this circuit, we have measured voltages and currents under different loadings. To this end, we powered the circuit using a variable DC power supply furnished with adjustable limiting-current control. We set the output voltage to ±28V and limit the output current to 0.6A. In the first place, we measure the no-load power consumption, that is found to be 3.4 W. This is mainly attributable to the three LM675 op amps since, according to datasheet [9], this op amp has a supply current of the order of 20mA for ±28V, thus adding to approximately 3W. The output voltage of the present 3P-generator was observed to be approximately 12V AC with respect to ground. Furthermore, this value appeared to be fairly constant all along the measurements, indicating that the circuit is indeed stable and equipped with output impedances much smaller than the loads used in the present measurements.

Table I summarizes the results of such measurements. The first column shows the load, the second the connection type, namely wye (Y) or delta (Δ). The third column denotes the power delivered from the CC supply to the circuit and, the fourth column shows the power delivered by the generator to the loads. The latter is obtained by measuring the line voltages and current and calculated using expression $P = \sqrt{3} I_L V_L \cos\varphi$, where $\cos\varphi$ is the cosine of the current-voltage phase shift φ. In order to determine φ, the time-difference between line voltage (V_L) and current (I_L) is measured by using the oscilloscope.

Load	**Connection**	**P_S (W)**	**φ (deg)**	**P_{out} (W)**	**Efficiency (%)**
3×470 Ω resistor	Y	5.6	0	0.92	16 (41)
	Δ	9.5	0	2.9	28 (43)
3×150 Ω resistor	Δ	21.8	0	8.0	37 (43)
3P-Motor	Y	10	67	1.7	17 (25)
	Δ	22	72	2.6	12 (14)

Table I. Power received from the DC power supply (P_S) and delivered to loads by the 3P-generator (P_{out}).

Notice that the efficiency is defined as $\mathbf{P_{out}/P_S}$, whereas the numbers enclosed in parenthesis denote efficiencies calculated after subtracting the no-load power of the circuit to the corresponding $\mathbf{P_S}$. It is worth commenting that the low efficiency that seems to have the proposed circuit is nonetheless acceptable for the push-pull output stage under the operating conditions as those in this generator. In fact, if one produces a 12V AC output (respect to ground) out from a 28V DC, using standard arguments one easily shows that the efficiency can hardly be larger than 43%.

4 Conclusion

A fully analog, low-cost, three-phase power supply is built. It is based in an op amp phase-shift oscillator plus three power stages. The latter are three push-pull stages inside a feedback loop which determines the voltage gain. This circuit was proven to work remarkably well for classroom demonstrations of three-phase electric power. This configuration also illustrates the advantages introduced by negative feedback: the voltage gain stabilization and the reduction of non-linear (cross-over) distortion, as well as the use of a source-degeneration configuration which improves thermal stability. With regard to the efficiency, it is clear that this circuit may not compete with those based on transistors working in switching mode. However, it must be remarked that, considering the simplicity and the low cost, the proposed circuit is fairly efficient, reaching up to a 43% with resistive loads. This efficiency is, on the other hand, nearly the same as the maximum figure one can expect from the operating conditions of the proposed circuit.

References:

[1] S.A. Shirvasar, B.A. Potter and I.M.L. Ridge, Three-phase machines and drives – Equipment for a laboratory-based course, I*EEE Transactions on Education* **49**, No.3, 2006, pp. 383-388.

[2] W.H. Baird and M.L. Jaynes, Low-voltage polyphasic circuits. *Am.J. of Physics*, **78**, No.5, 2010, pp. 499-502.

[3] T.F. Schubert Jr., F.G. Jacobitz and E.M. Kim, Exploring three-phase systems and synchronous motors: A low-voltage and low-cost experiment at the sophomore level, *IEEE Trans. on Educ.* **54**, No.1, 2011, pp 67-76.

[4] J. Bayard, Three-phase, voltage controlled sinusoidal oscillator, *Rev. Sci. Instr.* **73**, 2002, pp. 1914-1918.

[5] A. Sedra, K.C. Smith, *Microelectronic Circuits*, Oxford University Press, 1997.

[6] A.R. Hambley, *Electronics*, Prentice Hall, London, 2000.

[7] J.M. Jacob, *Power Electronics: Principles and Applications*, Delmar Cengage Learning, 2001.

[8] P. Horowitz and W. Hill, *The Art of Electronics*, 2nd. Edition. Cambridge University Press (1989).

[9] LM675 datasheet provided by Texas Instruments on the following Webpage: http://www.ti.com/lit/ds/symlink/lm675.pdf