CHAPTER 2

Historical Development of Magnetic Amplifier Circuits.

The history of saturable-reactor devices and magnetic amplifiers is about 50 years old and begins in 1901 when C.F. Burgess and B.Frankenfield disclosedthe early use of various forms of d-c-controlled saturable reactors for the "regulation of electric circuits" and described different types of con control-circuit decoupling means, as follows: series impedance, three-legged and four-legged cores, hollow annularcores, and magnetic "cross-valve" core arrangements. This disclosure, however, makes no claims regarding amplifying properties.

In 1901, R.A. Fessenden described the basic idea of using a saturable reactor in a "wireless signaling" system as a magnetic modulator in such a way that when the current in the microphone circuit "is modified or changed by speaking into the transmitter, the permeability of the core is correspondingly changed or modified, thereby producing a corresponding change or modification in the self-inductance and a change in the frequency of the natural period of vibration of the sending-conductor.

At the same time, H.J. Ryan devised a method for the measurement of large direct currents that employs a saturable transformer for comparing the values of large and small direct currents in terms of the ratio of transformation and the reading of the instrument used for measuring the small current.

This method is based upon the followingpprinciple: Where two coils of similar dimensions carrying direct current are placed side by side and linked with a closed magnetic core, the permeability of the core for alternating magnetic flux will be a maximum when the ampere-turns of the two coils are equal and opposite. By using this null method, it was possible to measure large direct currents in the range from 100 to 1,000 amp with an accuracy of about $\pm$ 0.5 per cent.

In 1913 an important advance was made by E. Besag, who introduced the combination of a twin-type saturable-reactor arrangement with direct-indicating instruments and recorders for measuring large direct currents by means of the magnetomotive force around the d-c conductor, without using giant-size shunt resistors, which are very expensive and difficult to cool. The a-c windings of the two saturable reactors are connected in series and to an a-c power supply, and the alternating current flowing through these windings is measured with an ammeter, which is calibrated in d-c units, to indicate directly the direct current to be measured.

Very important development started in the period 1918 when E.F.W. Alexanderson devised a method of modulating high-frequency alternating currents from one of his alternators so that its current could be used for transatlantic radio telephony. The corresponding disclosures comprise:

1. Early illustration of external-feedback means

2. Control-circuit decoupling means employing two cores, also four-legged and eight-legged cores
3. Early claim of off-resonant principle for increased gain
4. Frequency-discriminating means in a-c power-supply and control circuits
5. Early illustration of cascaded magnetic-amplifier stages
6. Means for utilizing a single winding for the combined functions of saturation control, d-c bias, and as the reactance winding of a d-c saturable reactor

Independently, in 1913, special forms of magnetic modulators were developed in Germany by L. Kuhn, M. Osnos, and L. Pungs. In 1915, G.W. Elmen described (1) an early Wheatstone-bridge circuit employing a signal-controlled saturable reactor in one arm, (2) novel control means by controlling the amount of agitating magnetomotive force to obtain variable hysteris-effect reduction, and (3) a hollow annular magnetic core for circuit decoupling. In 1916 and 1917, R.V.L. Hartley disclosed a fundamental push-pull magnetic modulator and a d-c saturable transformer with ultra-carrier-frequency magnetomotive-force means for hysteresis-effect reduction.

An early full-wave d-c load saturable-reactor circuit with internal feedback (self-saturating circuit) and control by d-c saturating windings was described in 1919 by J. Jonas. In 1928 to 1930, various forms of magnetic amplifiers with external-feedback circuits and some types of balanced circuits (zero output for zero control signal) were disclosed by

P.H. Dowling. The fundamental negative-resistance magnetic amplifier was introduced in different forms by K. Heegner (1925) and E. Peterson (1930).

In 1930, A.J.Sorensen and P.H. Dowling introduced (1) an early Wheatstone-bridge-type magnetic amplifier (the four reactance arms of the bridge are the four reactance windings on two three-legged reactors) and (2) a group of interesting push-pull (balanced) magnetic-amplifier circuits.

The recent historical development is considered to be the practical result of combined efforts and achievements in the following fields of electrical engineering:

1. The introduction of high-permeability nickel-iron-alloy core materials

2. The possibility of manufacturing efficient and reliable dry-disk rectifiers

3. The development of push-pull feedback circuit for flux gate magnetometers and magnetic servo amplifiers.

Since 1930, this development has been greatly increased, both in the United States and abroad. Some of the most important advances will be characterized in the following historical survey comprising the period from 1930 up to date.

A. Boyajian and C.G. Suits disclosed various improvements (non-linear novel external feedback circuits, etc.) P. Thomas and A.S. FitzGerald devised various single-stage and multistage types of magnetic amplifiers (neutral type and push-pull type) to be used in connection with relay devices or reversible motor arrangements. F.G. Logan and M.A. Edwards disclosed various types of self-saturating circuits with a-c or d-c load. E.T. Burton and C.W. La Pierre described several "second-harmonic" types of magnetic amplifiers and flip-flop circuits. A.L. Whiteley and L. C. Ludbrook described several half-wave self-saturating push-pull circuits to be applied with relays or thyratrons.

In 1937, W.Kramer revealed that properly rated saturable reactors with nickel-iron-alloy cores, preferably with rectangular-hysteresis-loop core material, have inherent current-transformer characteristics and that the ratio between the "primary" direct current to be measured and the average value of the rectified "secondary" current is equal to the ratio between the secondary and primary number of turns on the cores. The current-transformer character of this arrangement is to a certain extent independent of variations in magnitude, frequency, and waveshape of the a-c source. Furthermore, it has been proved by Kramer that by suitably designing the arrangement, the rectified average value of the alternating current is not only proportional to the direct current but to some extent will even have a similar oscillographic variation when the direct current varies, owing to a superimposed a-c component.

These arrangements, which are primarily intended for measuring large direct currents in the range from 100 to 10,000 amp, may equally well be used for measuring high direct voltages (W.Kramer,1938). The only difference will be that the direct voltage to be measured must first be translated, by means of a series resistor, into a direct current proportional to the voltage. This current will be of a magnitude which necessitates employing d-c windings with a large number of turns.

Kramer's fundamental development work attracted the attention of numerous investigators, resulting in further research and improvement. Pioneer work on saturable-reactor arrangements, without or with feedback, was carried out by T. Buchhold, A.U. Lamm, S.E. Hedstrom, B. Nordfeldt, K.M.H. Forssell, and U. Krabbe. In the Scandinavian countries the rather long expression "saturable reactor" has been replaced by the word "transductor." Many techniques involving special combinations of saturable reactors and dry-disk rectifiers for supplying controllable d-c power from single-, three-, and six-phase networks in place of the conventional mercury-arc-rectifier systems have been developed by Allmanna Svenska Elektriska Aktiebolaget (ASEA) personnel. These techniques are particularly suitable for installations with large power outputs.

The extensive development of magnetic-amplifier techniques in Germany during the period from 1937 to 1945 was based upon the fact that there are certain military applications for amplifiers of electric signals which require that these amplifiers possess unusual durability, simplicity, and reliability. Pioneer work on the single-phase push-pull type of saturable-reactor circuit as a magnetic amplifier for various servo applications (e.g.,in autopilots, blind-approach systems, remote-control positional servomechanisms, and computer circuits) and as a flux-gate magnetometer was carried out by G. Barth and his staff. These devices were designed to operate at ambient temperatures between +70 and -60° C for supply voltages of 30 to 40 volts and frequency ranges of 400 to 600 cps. Both naval and air-force equipment was produced by Siemens Apparate & Maschinen (SAM) personnel. Of course, disclosures conncerning this wartime development were limited to internal reports, and no theoretical design principles were published. This restriction of German publications in the field of magnetic amplifiers led some to believe that, although excellent results were obtained, design and development progressed almost entirely by trial and error.

Early in 1944, G.S. Hudson initiated work on magnetic amplifiers at the Royal Aircraft Establishment, which has been concerned mainly with amplifiers designed to operate from a 400-cps power supply. This work and detailed examination of German designs may have reawakened interest in magnetic amplifiers in England.

Theoretical and experimental studies of the series-connected magnetic amplifier with external feedback have been published by S.E. Tweedy, A.G. Milnes, and by H.M. Gale and P.D. Atkinson. Furthermore, several studies in this field have been presented by E.H. Frost-Smith, J.H. Reyner, and F.E. Butcher and R. Willheim.

Finally, it is interesting to note that standardizing groups of the American Institute of Electrical Engineers are now working on definitions and methods of expressing the performance characteristics of magnetic amplifiers.