current will not cause, in the majority of U.S. houses, nuisance tripping due to leaky wiring [1].

THE DIFFERENTIAL TRANSFORMER

Differential transformers used in Europe for the direct tripping 30 mA GFI devices generally employ 0.10 mm supermalloy tape [6]. The cores are about 25 mm in diameter with an area of 1 cm^2. The material is heat treated for high maximum permeability ($\mu_{max} \sim 200{,}000$) so that a fault current of 30 mA in one or more turns will magnetize the core to inductions of 2,000 to 5,000 G providing sufficient output energy for a direct tripping relay. Since GFI's are normally installed outside the temperature-controlled living area, the high maximum permeability is usually stabilized over the temperature range from -15°C to +45°C.

Puzei [7], Pfeifer [8] and later English and Chin [9] have described temperature range stabilization of high-permeability nickel alloys such as supermalloy (80.25 Ni, 4.25% Mo, Re-Fe) by baking the alloy at lower than normal temperatures where increased Ni_3Fe ordering will take place. This process shifts the magnetocrystalline anisotropy $K_1 = 0$ to a lower temperature, so that the permeability peak $\mu(T)$ occurs at lower temperature, normally just below the temperature range of the GFI operation.

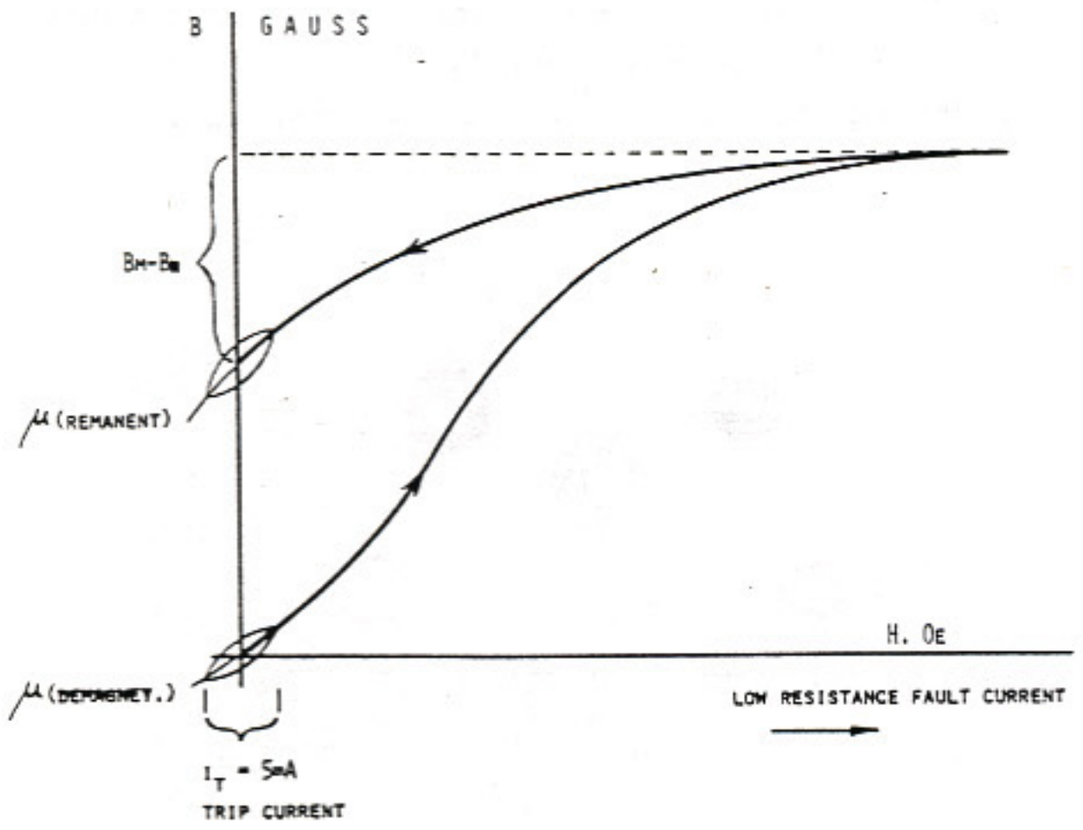

Fig. 4. Permeability of differential transformer in demagnetized state and after low resistance fault test.

However, hysteresis loop characteristics also change. At temperatures at which $K_1 < 0$, above the $\mu(T)$ peak, the material has a more square hysteresis loop that, as will be shown, limits its usefulness in differential transformers for measuring a fault current of 5 mA. Such fault current magnetizes the core to inductions of less than 120 G. On the other hand, low resistance faults (shorts against ground) will magnetize the core to saturation (Fig. 4) and leave if after tripping the GFI in the remanent state. The permeability in remanence at $\Delta I \sim 5$ mA is always lower than the initial permeability. This is especially true when the material has been heat treated at lower baking temperatures so that the core operates at $K_1 < 0$. A great change of permeability would result in increased trip currents of the GFI after a low resistance fault which is not permissible.

Cores with a round hysteresis loop exhibiting the least change in permeability from the demagnetized to the remanent state are, therefore, essential for reliable GFI operation at 5 mA trip current.

RINGS VS TAPE WOUND LAMINATIONS

The differential transformer is not only exposed to fields generated by the load current differential it must measure, but also to spurious fields of other current carrying wires within the circuit breaker and its vicinity. The transformer, therefore, must be self-shielding to the highest degree (i.e., stray fields at the core have to split exactly in half, see Fig. 5) so that no output voltage is generated. This requires a high and uniform permeability $\mu(\alpha)$ over the circumference of the core.

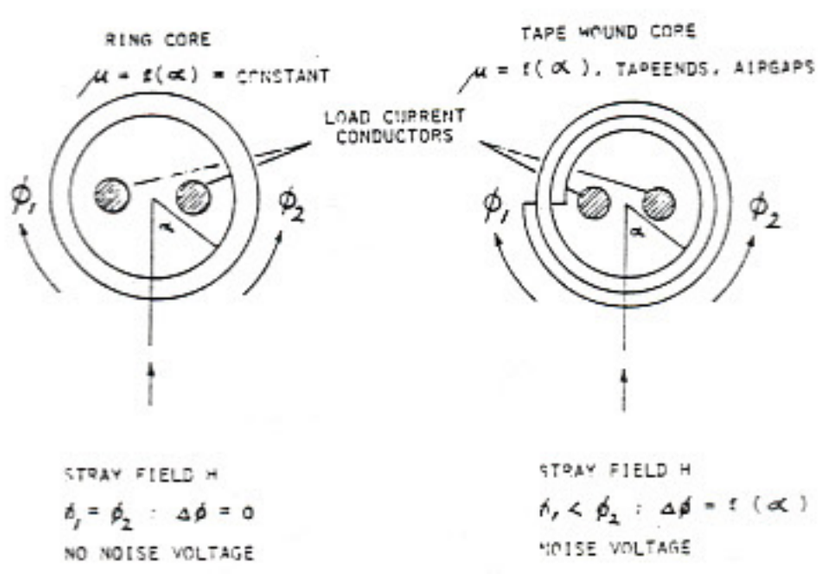

Fig. 5. Noise voltages of ring and tape wound cores.

First experiments with 0.05 mm and 0.025 mm thick tape showed very high and uncontrollable noise voltages. These can be attributed to air gap and tape end effects in the wound core which change the reluctance and, therefore, the permeability. They are especially troublesome in small cores of short mean path lengths. Stamped ring laminations, having no air gaps, eliminate this noise problem entirely. The requirements listed in Fig. 6 were established for cores fitting into existing USA circuit breakers (about 2.5 X 7.5 X 7.5 cm).

The high permeability $\mu_{40} > 40{,}000$ over the wide temperature range from -35°C to +66°C in the demagnetized and remanent state can only be obtained with carefully selected vacuum melted supermalloy in which the $\mu(T)$ peak is relatively flat. To achieve the proper differential transformer characteristics, very strict process control is also required, which ensures

A.	OPERATING RANGE:	TEMPERATURE:	-35°C TO +66°C	
		TRIP CURRENT:	5mA (RMS): N_p = 1, H~2.5 mOE	
		LOW RESISTANCE FAULT CURRENT: > 120 AMPERE		
B.	MAX. DIMENSIONS:	OD (MM)	ID (MM)	HEIGHT (MM)
	AS WOUND (1000) TURNS	15	5	7
	BARE CORE	12.7 (.500")	9.5 (.375")	3.2 (.125")
C.	PERFORMANCE:	OUTPUT VOLTAGE:	V OUT~12 MV/1000 TURNS	
		NOISE VOLTAGE:	LESS THAN 10% OF V OUT	
		PERMEABILITY:	40,000 < μ_{40} < 75,000	
		(WHEN MEASURED IN DEMAGNETIZED OR REMANENT STATE)		

Fig. 6. Requirements for differential transformer.