Working Modes of a Transformer

Simona Filipova-Petrakieva

***Abstract*—The main function of the transformer is to convert AC voltage from one value to another. Its normal working mode is to increase or decrease the AC voltage. When its primary and secondary windings have equal turns, it is used to galvanically separate of the consumer from the power supply. Depending on the connection of the secondary winding to the load, it works in modes of increasing or decreasing the output voltage - booster or buck transformer, respectively. In these modes, the design of the transformer ensures less power than in normal use. It is absolutely forbidden to connect the primary and secondary windings to the power supply in parallel each other and in parallel of the supplied voltage without reactive passive elements in series of them. This is only possible for primary and secondary windings with equal number of turns. In the present work, a detailed analysis of these modes is provided. The stress is on their specific character.**

***Keywords*—working modes of transformer – accepted and unaccepted, booster transformer, buck transformer**

I. Introduction

A transformer is a device that converts an alternating-current (AC) voltage from one value to another. It consists of at least two windings (primary and secondary, with w_1 and w_2 turns, respectively) mound on a common magnet core. (Fig. 1.) [1].

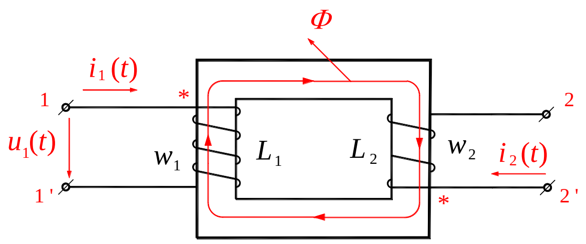


Fig. 1. Ideal transformer.

After supplying a voltage to the primary side of a transformer, a magnetic field with magnetic flux Φ is created. The lines of this field are continuous curves, closing in the magnet core. The main part of them is covered by the secondary winding and produces an induced ElectroMotive Force (EMF) according to the Faraday's law.

As one of the main components in electrical networks, along with busbars, rotating machines, and transmission and distribution lines and cables, transformers allow operation in different modes depending on their connection to other devices. This will ensure normal functionality of the entire electrical power system, but only if the transformers are properly connected to the load. Different schemes for electrical power system protection are discussed in [2]. They include current-differential, phase comparison, distance and travelling wave.

For the normal working of the transformer, the connection of its windings to the network or to the circuit of the respective appliance or device is of utmost importance. This is the main reason why this article discusses and analyses the acceptable and unacceptable schemes and modes of operation of the transformer.

In the analysis of a transformer, the fluctuation of the magnetic field in its magnetic core is the interesting aspect. Such research has been performed in [3]. This work does not consider the magnetic field in a transformer, but discusses possible and unacceptable working modes of the transformer under different connections of its primary and secondary windings in real device circuits.

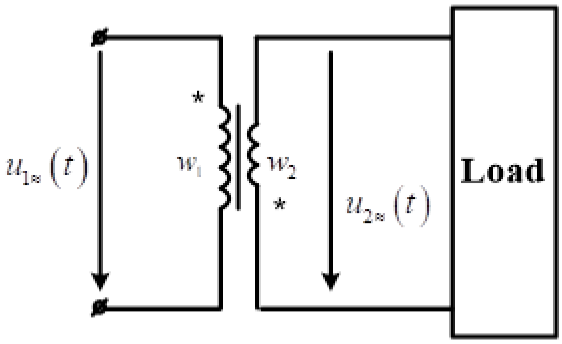
In this paper, an overview and analysis of various real existing circuit solutions of transformer inclusion in electrical circuits is presented. It is organized as follows: in the next Section 2, acceptable modes of transformer operation incorporated in various real electrical devices are discussed. Emphasis is placed on its basic (normal) working mode either as booster, buck transformer or as galvanic separation. In Section 3, unacceptable transformer winding connections are mentioned and their consequences are explained. The paper concludes with concluding remarks on the applicability of the various circuit solutions in real working devices.

II. Working Model Of The Transformer - Schemes

The main working modes of the transformer are the so-called normal modes. In these, the primary and secondary windings are galvanically separated from each other (Fig. 2). Energy is transmitted by inductive path and switching proceeds normally.

2.1. Normal working mode of a transformer

The scheme of the normal working modes of the transformer is shown in Fig. 2.



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Simona Filipova-Petrakieva is with the Technical University of Sofia, Sofia, 1000, 8 Kl. Ohridski Blvd, Bulgaria (petrakievas-te@tu-sofia.bg)

Fig. 2. Scheme of the normal working mode of the transformer.

Depending on the number of turns of transformer's windings, it works in the following modes:

If $w_2 < w_1 \;\Rightarrow\; u_{2\approx}(t) < u_{1\approx}(t) \;\Rightarrow\;$ buck transformer.
If $w_2 > w_1 \;\Rightarrow\; u_{2\approx}(t) > u_{1\approx}(t) \;\Rightarrow\;$ booster transformer. (1)

2.1a. Working mode of the transformer for galvanic separation

A partial case of the normal modes, mentioned above, is the situation where the transformer is used to galvanically separate the consumers from the supply voltage. The principal circuit is the same as the one shown in Fig. 2. Here, it is essential that

$$w_2 = w_1 \;\Rightarrow\; u_{2\approx}(t) = u_{1\approx}(t) \qquad (2)$$

In these working modes of the transformer, no special schemes are required to control the switching of the secondary winding to the consumer.

An exception is the autotransformer. It has only one winding, part of which is used simultaneously by both the source and the consumer. This type of transformer is shown in Fig. 2a. and 2b. as a buck and a booster autotransformer, respectively – according to Eq. (1), [4]). As a result, one part of the energy is transmitted via the inductive path and another via the galvanic path.

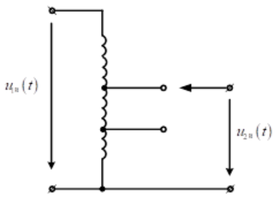

Fig. 2a. Buck autotransformer.

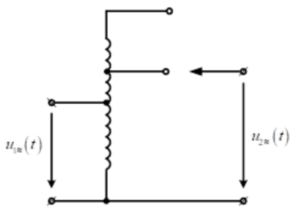

Fig. 2b. Booster autotransformer.

In real applications, there are cases where transformers work in more specific modes. In these cases, the connection of the primary and secondary windings with a common point is realized. The resulting circuit is connected either to the consumer, or to the supply network, as it is shown below.

The specific feature that distinguishes this type transformers is that they have a connection between two of their terminals and in this case no galvanic separation of the consumer from the network is realized.

2.2. Serial connected transformer's coils connected to the load

In this case, the transformer can work in two modes - as a booster or a buck transformer. Then the voltage, supplied to the load, increases or decreases with respect to the network one.

2.2a. Booster transformer

An electrical circuit of this transformer is shown in Fig. 3a. In this case, the voltage supplied to the consumer $u_{\approx}(t)$ is greater than that of the supply network voltage $u_{1\approx}(t)$, since the two windings are connected in series and in phase, i.e. the voltages are added each other:

$$u_{\approx}(t) = u_{1\approx}(t) + u_{2\approx}(t) \qquad (3a)$$

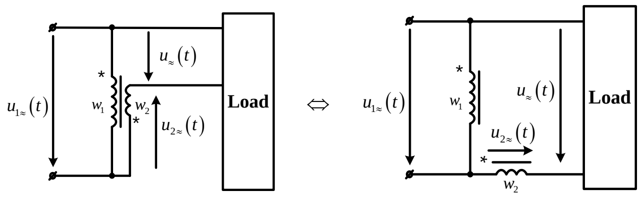

Fig. 3a. Booster transformer.

This scheme is used in cases where the consumer is located in an area of reduced voltage, e.g. at the end of the transmission network, where due to the high active resistance of the current-carrying conductors an increased voltage occurs. With this scheme, the necessary compensation is achieved.

2.2b. Buck transformer

An electrical circuit of this transformer is shown in Fig. 3b.

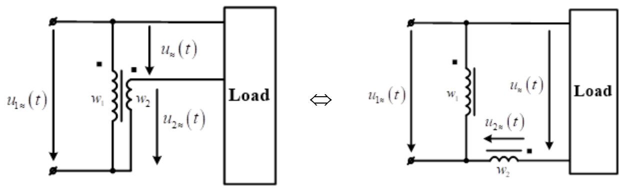

Fig. 3b. Buck transformer.

In this case, the voltage supplied to the consumer $u_{\approx}(t)$ is less than that of the supply network voltage $u_{1\approx}(t)$, since the two windings are connected in series and in antiphase, i.e. the voltages are subtracted each other:

$$u_{\approx}(t) = u_{1\approx}(t) - u_{2\approx}(t) \qquad (3b)$$

Working the transformer in the modes mentioned above - as a booster or buck transformer requires more complex secondary winding switching schemes. This is due to the fact that inductive circuits are switched in where is stored energy and there is a possibility of unacceptable overvoltages when open circuit modes arise.

A very common real situation is that in remote places, such as small villages, consumers receive a lower supply voltage. This can be quite different from the standard acceptable variation of its effective value: +/- 10 % of 230 *V* and can reach up to 150 *V*. It is then necessary to increase it. One solution for this is by using booster transformers. Such solution is proposed in [5]. It increases the supply voltage by 5 - 35 % in 5 % steps. This is implemented by three transformers whose secondary windings are connected in series to the supply voltage according to Fig. 3a.

Buck transformers are used for decreasing of the electrical energy demand and its effectively use. In recent years, this problem has become essential as the consumption of electrical energy is continuously increasing and the planet's energy resources are decreasing. A simple and reliable solution to this problem is proposed in [6]. In it, the secondary winding of the transformer is connected in series in antiphase to the primary winding and the load is connected to it (Fig. 3b.). This solution can be applied at any time of the day when reduced power consumption by consumers is acceptable. In particular, it can be used in the night in street lighting systems, billboards, household appliances, industrial production, etc.

2.3. Serial connected transformer's coils connected to the power supply

In this case, again, the transformer can work in two modes - as a booster or a buck transformer. These are not typical of the practice. The booster transformer mode is critical and is mainly considered theoretically. The buck transformer mode is acceptable.

2.3a. Booster transformer

An electrical circuit of this transformer is shown in Fig. 4a.

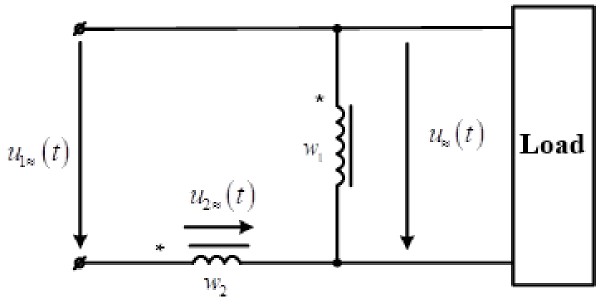

Fig. 4a. Booster transformer.

In this case, the voltage supplied to the consumer $u_{\approx}(t)$ is greater than that of the supply network voltage $u_{1\approx}(t)$, since the two windings are connected in series and in antiphase, i.e. the voltages are added each other:

$$u_{\approx}(t) = u_{1\approx}(t) + u_{2\approx}(t) \tag{4a}$$

2.3b. Buck transformer

An electrical circuit of this transformer is the same as that from Fig. 4a. with the only difference that the ends of the w_2 are reversed. As a result, the decreased voltage is supplied to the load $u_{\approx}(t)$. The circuit studied is shown in Fig. 4b.

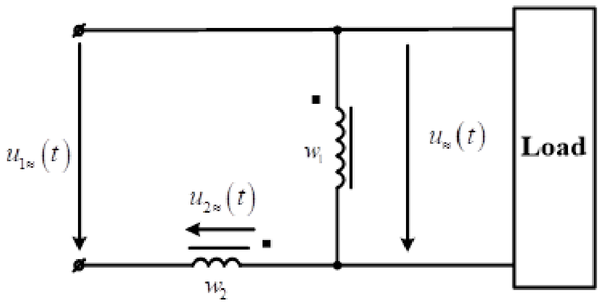

Fig. 4b. Buck transformer.

In this case, the voltage supplied to the consumer $u_{\approx}(t)$ is less than that of the supply network voltage $u_{1\approx}(t)$, since the two windings are connected in series and in phase, i.e. the voltages are subtracted each other:

$$u_{\approx}(t) = u_{1\approx}(t) - u_{2\approx}(t) \tag{4b}$$

III. Unacceptable Transformer's Windings Connection Schemes

There are modes in which it is completely unacceptable for the two primary and secondary windings with different numbers of turns to be connected in parallel each other (either in phase or in antiphase) and for the network voltage to be supplied directly to them without reactive passive elements. This situation is shown in Fig. 5.

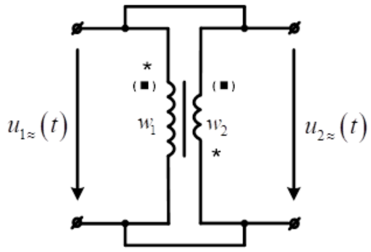

Fig. 5. Parallel connection of the transformer's windings with different turns each other and to the power supply – absolutely FORBIDDEN.

In this case, a breakdown will occur in the device containing the transformer will certainly break down. The connection, shown in Fig. 5, is acceptable ONLY in the following two cases:

3.1. Primary and secondary windings with equal turns and connected in phase (Fig. 5a.)

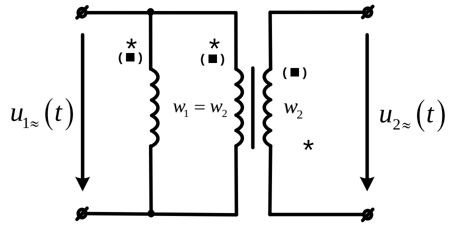

Fig. 5a. Primary and secondary windings with equal turns, connected in parallel each other and to the power supply.

$$\text{If} \quad w_1 = w_2 \quad \Rightarrow \quad u_{1\approx}(t) = u_{2\approx}(t) \tag{5}$$

This mode is used in the case of a single winding (on the primary side of the transformer) of two conductors of the coils. This provides more power transferred to the load.

This mode is used in the case of wrapping one of the two windings of the transformer (primary or secondary) by two conductors. It is then required when the cross section of one conductor is not sufficient and two conductors coiled in parallel are used. This provides higher power transferred to the load.

3.2. A capacitor in serial of the primary winding is switched (Fig. 5b.) [7]

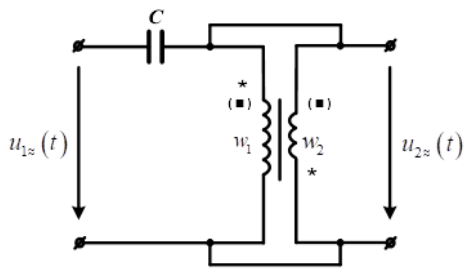

Fig. 5b. Parallel connection of primary and secondary windings to the power supply using a capacitor in the primary side.

Connecting a capacitor in series to the power supply functions as a current limiter. The total current is multiplicative inverse (reciprocal) to the inductive reactance of each of the windings.

This scheme of the transformer is only theoretically considered. It is not applied in praktics.

IV. Conclusion

In the current paper, the main features of transformers with galvanic and non-galvanic winding separation are discussed. In normal mode, depending on the turns of the windings, it can work as a booster $\left(w_2 > w_1\right)$, buck $\left(w_2 < w_1\right)$ transformer or in galvanic load separation mode $\left(w_2 = w_1\right)$.

In serial connection of the windings without having additional passive elements in the circuit, the transformer work as booster or buck transformer.

Typical practical applications of the transformer are booster, buck and galvanic splitting modes, as well as series connection of its windings with a common point to the load. The booster and buck modes of the transformer in serial connection of the windings to the supply voltage have no practical application.

Parallel connection of the primary and secondary windings with different turns each other and to the supplied voltage is absolutely unacceptable situation. This connection is acceptable only in the following two cases:

- Only, when two windings have equal turns. This mode uses to creating a single winding (on the primary side of the transformer) from two conductors of the coils, which ensure more power transferred to the load.
- Primary and secondary windings have different turns, but a transformer is separates by the supplied voltage by a capacitor, balancing the voltages on the transformer's windings.

References

[1] A. J. Pansini, "Electrical Transformers and Power Equipment", 3rd edition, The Fairmont Press, USA, ISBN: 0-88173-311-3 FP, 394 p., 1999.

[2] A. Wright, C. Christopoulos, "Electrical Power System Protection", 1 st edition, Springer-Science+Business Media, Chapman & Hall, ISBN: 978-1-4613-6341-5, e-ISBN: 978-1-4615-3072-5, DOI: 10.1007/978-1-4615-3072-5, 530 p., 2012.

[3] A.Yanev, A. Chervenkov, "Numerical modelling of the magnetic field distribution in single-phase single-core transformer", Proceedings of 12th Summer school „ADVANCED ASPECTS OF THEORETICAL ELECTRICAL ENGINEERING", 13-14 Sept. 2018, Sofia, Bulgaria, ISSN: 1313-9487, pp. 71-77.

[4] Colonel Wm. T. McLyman, "Transformer and Inductor Design Handbook", 4nd edition, CRC Press, Taylor & Francis Group, an informa business, USA, ISBN-13: 978-1-4398-3688-0, 2011.

[5] Y. Shopov, S. Filipova-Petrakieva, "Supply voltage control using booster transformers", 14th International Conference BulEF'2022, 14-17.09.2022, Varna, Bulgaria, ISBN: 978-166549026-9, IEEE Catalog Number CFP22BUL-ART, 2022, Conference ID in IEEE Xplore: 56479X, DOI. 10.1109/BulEF56479.2022.10020198

[6] Y. Shopov, S. Filipova-Petrakieva, "Reducing power consumption using booster transformers", 15th International Conference BulEF'2023, 16-19.09.2023, Varna, Bulgaria, ISBN: 979-8-3503-2653-6/23, IEEE Catalog Number CFP23BUL-ART, 2023, Conference ID in IEEE Xplore: 59783X, DOI. 10.1109/BulEF59783.2023.10406240

[7] G. I. Atabekov, et. al., "Theoretical basis of Electrical Engineering", 2nd & 3rd part, 2nd edition, Vaishaia shkola, Moskva, Russia, ISBN: , 600 p., 1966. (in Russian)