Developing an electrical power system of a mobile electron beam accelerator to treat wastewater and industrial effluents

Desenvolvimento de um sistema de energia elétrica de um acelerador móvel de feixe de elétrons para tratar águas residuais e efluentes industriais

DOI:10.34117/bjdv7n11-046

Recebimento dos originais: 07/10/2021
Aceitação para publicação: 04/11/2021

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ABSTRACT

The treatment of wastewater and industrial effluents by electron beam irradiation is a promising technique, however, not very widespread in Brazilian territory. The design and construction of a mobile unit by the Nuclear and Energy Research Institute, containing an electron beam accelerator of 700 keV and 20 kW is innovative to demonstrate the effects and positive results of this technology. The aim is to transfer the mobile unit to several companies with interest in liquid waste treatment, connect to the industry electrical system and start the ionization treatment process through electron beam. The mobile unit connection to the local electrical system may be a challenge due to the great diversity of voltages and distances involved, as well as the large injections of harmonic content generated by the electron beam accelerator that can affect sensitive loads in the industrial system. In this work, an analysis of the electrical power system of the mobile unit was made, regarding the interruption capacity, selectivity protection and adequate short circuit levels, in order to assure a greater reliability in the operation. At the end, the control panel of the mobile unit, simulations and measurements were carried out at the 1.5 MeV and 37.5 kW electron beam accelerator, installed in the Radiation Technology Center, demonstrating the necessity of applying a filter to reduce the measured harmonic distortion. The analysis of the mobile unit electrical power system was made, in order to assure a greater reliability in the operation.

Keywords: Industrial electron accelerator, harmonic distortion, electric power quality, mobile irradiation unit.

ABSTRACT
O tratamento de águas residuais e efluentes industriais por irradiação por feixe de elétrons é uma técnica promissora, porém, não muito difundida no território brasileiro. O projeto e a construção de uma unidade móvel pelo Instituto de Pesquisa Nuclear e Energética, contendo um acelerador de feixe de elétrons de 700 keV e 20 kW é inovador para demonstrar os efeitos e os resultados positivos desta tecnologia. O objetivo é transferir a unidade móvel para várias empresas com interesse no tratamento de resíduos líquidos, conectar ao sistema elétrico da indústria e iniciar o processo de tratamento de ionização através de feixe de elétrons. A conexão da unidade móvel ao sistema elétrico local pode ser um desafio devido à grande diversidade de tensões e distâncias envolvidas, assim como as grandes injeções de conteúdo harmônico gerado pelo acelerador de feixe de elétrons que podem afetar cargas sensíveis no sistema industrial. Neste trabalho, foi feita uma análise do sistema de energia elétrica da unidade móvel, quanto à capacidade de interrupção, proteção de seletividade e níveis adequados de curto-circuito, a fim de assegurar uma maior confiabilidade na operação. No final, o painel de controle da unidade móvel, simulações e medições foram realizadas no acelerador de feixe eletrônico de 1,5 MeV e 37,5 kW, instalado no Centro de Tecnologia de Radiação, demonstrando a necessidade de aplicar um filtro para reduzir a distorção harmônica medida. Foi feita a análise do sistema de energia elétrica da unidade móvel, a fim de assegurar uma maior confiabilidade na operação.

Palavras-chave: Acelerador de elétron industrial, distorção harmônica, qualidade de energia elétrica, unidade móvel de irradiação.

1 INTRODUCTION

Wastewater and industrial effluents treatment by electron beam accelerator (EBA) is a promising technique. However, it is not widespread in Latin America and the Caribbean. The design and construction of a Mobile Unit containing an EBA (0.7 MeV and 20 kW) by the Nuclear and Energy Research Institute is innovative to demonstrate the effects and positive results of this nuclear technology. The Mobile Unit connection to electrical systems in industries may be a challenge due to the great diversity of voltages and distances involved, as well as the large injections of harmonic content generated by the EBA [1].

In modern times, most industries need to treat contaminated solid, liquid and / or gaseous wastes during the manufacturing process steps. Inadequate treatment of this waste may cause damage to both aquatic and human life, as well as allowing the application of high fines by environmental agencies [2].

The treatment of industrial waste is classified according to the techniques used. They may be by means of chemical reactions (chemical), natural processes (biological) or by processes of separation (physical). The last one includes elimination techniques by ionizing radiation produced by an electron beam, which can have many effects according to the electron-related energy. For the treatment of industrial effluents, the objective is the degradation of organic compounds, often with a high degree of toxicity, in order to obtain the least possible environmental impact, which is minimizing the gases generated throughout the process and allowing the reuse of the treated effluent. Because it is a fast and non-selective technique, its speed is superior when compared to traditional methods, what allows achieving cost-effective advantages when used for large volumes [3].

The EBA is not widespread in Brazil, due to several factors, among them the lack of technology diffusion, national manufactures and the high cost required. In this scenario, the Nuclear Energy Research Institute has consolidated partnerships with national (Truckvan Industry and NUCLEP) and international (EBTech Co., ltd.) companies, aiming at the development of a mobile beam irradiation unit which would provide assistance in the treatment of industrial effluents, disseminating this technology in several areas of Brazil. Besides Brazilian Innovation Agency (FINEP), the International Atomic Energy Agency supports the IAEA TC Project BRA1035 - Mobile irradiation unit with an electron accelerator to treat industrial effluents for reuse.

The mobile unit consists of a truck whose cargo compartment accommodates all the necessary equipment to treat solid, liquid or gaseous waste by electron beam including a control room, hydraulic units, ventilation and refrigeration systems, transformer and an electric distribution panel.

2 OBJECTIVE

In this study, an analysis of an electron beam accelerator power system (1.5 MeV and 37.5 kW) was made in order to develop and find out all necessary electrical equipment and components to project and build a Mobile Irradiation Unit (0.7 MeV and 20 kW), with great flexibility and reliability for the treatment of wastewater and industrial effluents.

3 ELECTRICAL CONNECTION VOLTAGE

The Mobile Irradiation Unit will be developed to move around Brazil territory. Therefore, it should be versatile for the existing electrical connection types, varying voltage levels and connection distances. It was evaluated as a connection method, providing a large scope of use, low operating costs and easy installation. Basically, the methods analyzed were connections at low and medium voltages, or used a diesel generator.

After evaluating each method advantages and weaknesses, a low voltage option was settled due to a greater range of uses and ease of connection with 220/380/440 Volts, commonly widespread in Brazilian industries. In addition to the low voltage connection, the diesel generator necessity was evidenced after in situ visits, in medium-sized industries that could not support the extra load required by the Mobile Unit. Consequently, the only way of connection would be the use of a diesel generator.

Due to the constructive nature of the EBA, based on multi-stage voltage multiplier circuits, the generation of harmonic currents in the electric network occurs constantly. Therefore, evaluation to guarantee the energy quality is required, not affecting the other loads connected to the network, in which the Mobile Unit will be installed.

For the transformer design of the Mobile Unit, the percentages measured in the RDI industrial electron accelerator, under the same electron energy conditions, were considered.

4 MOBILE EBA LOADS

All required loads were previously studied so that the transformer could be properly sized. Table 1 quantifies all necessary loads and their basic data, obtained directly by the manufacturers and from other IPEN-CNEN developers.

Table 1. Predicted electrical loads necessary for the Mobile EBA.

Equipment	Voltage (V)	Load (kVA)
Electron Beam Accelerator	3Ø - 380	33.33
Chiller cooling system	3Ø - 220	22.55
Control panel	1Ø - 220	2.17
Vacuum pump	1Ø - 220	2.09
Window cooling fan	3Ø - 380	5.89
Air circulation fan	3Ø - 380	5.89
Air conditioner, lighting and power plugs	1Ø - 220	5.31
Effluent circulation pump	3Ø - 380	16.85
Microcomputer, projector and instruments	1Ø - 220	5.43

5 ELECTRON BEAM ACCELERATOR

The electron beam accelerator foreseen to be used at the mobile unit will be manufactured by EBTech Co., Ltd. The model consists of a vertical mounted cylindrical tank filled with SF_6 (sulfur hexafluoride) gas, allowing compact dimensions for the accelerator. The high voltage rectifier is composed by an oscillator that transforms the network frequency to 400 Hz, followed by a high turn ratio transformer, which generates a 20 kVac voltage. The rectifier, then, doubles this voltage and converts to direct voltage, resulting in 40 kVcc, used by the injection controller and, finally, applied to the high voltage (cathode) terminal.

The acceleration tube consists of the high voltage filament and a heater located at the end of a 180 mm diameter ceramic insulator, where the electrodes are located, 21 mm apart from each other. The beam current generated by the circuit is controlled by the cathode temperature. The vacuum system is created by two pumps, located between the SF_6 dome and the scan horn. Under these conditions, electrons may be accelerated to a maximum energy of 0.7 MeV and 20 kW.

6 EBA HARMONIC ANALYSYS

It is known that, due to the constructive nature of the electron accelerator, based on multi-stage voltage multiplier circuits, the generation of harmonic currents in the electric network occurs constantly, requiring evaluation to guarantee the energy quality and, thus, not affecting the other loads connected to the network in which the Mobile Unit will be installed.

In order to facilitate the understanding and allow the characteristics of the load to be studied, it was proposed to analyze the power system of an Industrial Electron Accelerator installed in the Radiation Technology Centre, at IPEN-CNEN, model RDI DC 1500/25/4, with energy of 1.5 MeV, beam current 25 mA and beam power 37.5 kW.

For the measurement of the electrical parameters, a power quality meter was used, as shown in Figure 1. The current transduction was performed by current transformers with relation 400-5 A, class 0.3 C and 12.5 VA and the voltages were measured directly from the three-phase 440 V.

Fig. 1. Power quality meter used to measure harmonic levels of an EBA.

The non-linearity characteristic of the current and the voltage waveforms were verified, as well as the harmonic distortion of a similar industrial electron accelerator model RDI DC 1500/25/4 (1.5 MeV and 37.5 kW). The distortion levels obtained were compared with normative limits, where it was noticed an overcoming in all operation ranges. In Table 2, it is shown, in bold, the current harmonic distortion for the EBA, at nominal conditions (1.5 MeV and 15 mA).

Table 2. Harmonic values measured in the EBA
(1.5 MeV and 37.5 kW).

Harmonic Order	IEC 61000-3-4 Limit (%)	IEEE-519 Limit (%)	Measured (%)
3	21.6	12	2.09
5	10.7	12	**31.53**
7	7.2	12	4.26
9	3.8	12	0.36
11	3.1	5.5	**7.2**
13	2.0	5.5	0.19
15	0.7	5.5	0.22
17	1.2	5	**3.66**
19	1.1	5	0.51
21	≤0.6	5	0.11
23	0.9	2	**2.26**
25	0.8	2	0.62
27	≤0.6	2	0.1
29	0.7	2	1.54
31	0.7	2	0.68
35	≤0.6	2	1.13

The results evidence a necessity of harmonic filters (passive or active), tuned to 5, 11 and 17 frequencies, mainly for this EBA. For high harmonic frequencies, a simple high pass filter may be used to attenuate these values, not influencing the frequencies near the fundamental.

The Mobile EBA electrical system was modeled considering all loads required. The short circuit currents, validation of circuit breakers, graphical verification of the coordination and selectivity of current settings, plus calculation of the harmonic distortion ratio, were all calculated.

Cable sizing procedures were in accordance with Brazilian IEC 61000-3-4 and IEEE-519 standards [4,5]. The voltage used in the calculations was the minimum available (220 V), resulting in higher losses and larger sections.

The cable length has been set based on some industries visited, where 100 m would be enough for most customers, who wish to receive the mobile unit for wastewater and effluent treatments.

7 MOBLIE EBA POWER TRANSFORMER

The mobile unit power transformer is capital for many reasons, such as isolating the circuit against voltage surges, allowing different voltage levels connection, reducing short circuit levels and the harmonics influence at the electrical network.

Since the input voltage is not a clearly defined element due to the diversity of existing voltage levels, the transformer has to be designed with many ascenter-tap's to allow several voltage connections at primary winding, while maintaining a fixed voltage at 380 V side. In the presence of nonlinear loads, such as harmonics, there is an increased loss by Joule effect and additional losses in the iron.

The parameter that determines the transformer tolerance to harmonic contents is the "k factor" defined by the standards UL 1561-1994 and UL 1562-1994, according to the IEEE C57.110 guide [6]. A k=1 factor indicates that the transformer is sized to bear linear loads.

The definition of the k factor is shown in Equation 1.

$$FatorK = \sum_{h=1}^{\infty} \left(\frac{I_h}{I_R}\right)^2 h^2 \qquad (1)$$

In which h represents the harmonic order, I_h the harmonic current and I_r stands for the total current.

The harmonic distortion rate of the mobile unit electron accelerator is unknown and not reported by the manufacturer. Therefore, for the design of the transformer, the percentages measured in the industrial electron accelerator were considered, with energy of 1.5 MeV and beam power of 37.5 kW, under the same electron energy conditions. The total harmonic distortion measured for the accelerator was k=7.28.

As the calculation is based on the total percentage of loads and the EBA represents only one third of the total load, this factor is reduced to k equal 1.61. Due to this low value, it was suggested to acquire a transformer with a unitary k factor (k=1), but oversized, assuming extra losses generated by harmonic currents [7].

This concept, called *derating*, is considered by the IEEE according to Equation 2, in which PEC-R(pu) represents losses by eddy currents under nominal conditions and K the harmonic factor.

$$I_{MAX}(pu) = \left[\frac{1+P_{EC-R}(pu)}{1+(K)\cdot P_{EC-R}(pu)}\right]^{\frac{1}{2}} \qquad (2)$$

This value depends directly on the transformer design. For a 100 kVA transformer, the usual value is 500 W of empty losses and 2,900 W of total losses. Thus, the value of PEC-R (pu) results from the relation between the two values, or 0.17pu. Hence, Equation 2 is solved as shown in Equation 3.

$$I_{MAX}(pu) = \left[\frac{1+0.17}{1+(1.61\cdot 0.17)}\right]^{\frac{1}{2}} = 0.95 \qquad (3)$$

Therefore, supplying 100 kVA of load, considering the harmonic content of the electron accelerator, it will be required a power of 105.2 kVA to all loads from the mobile EBA. Figure 2 illustrates the final result of the transformer and switchboard manufacturing, developed for the mobile unit at IPEN-CNEN.

Fig. 2. Power transformer (a) and switchboard (b) developed for the mobile EBA at IPEN-CNEN.

(a)

(b)

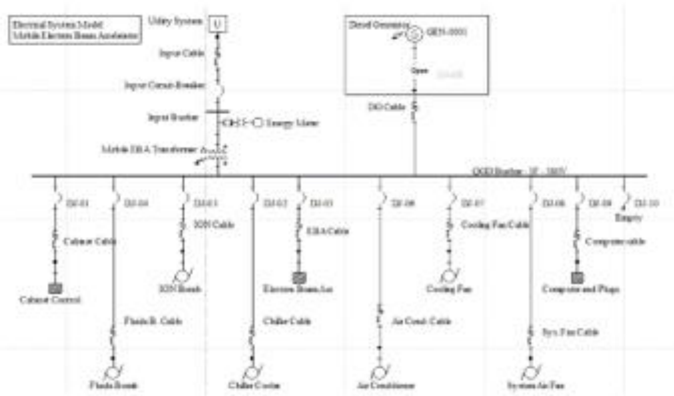
8 MOBILE EBA UNIT SWITCHBOARD

The upstream circuit breaker needs to be purchased with adjustable LSI (Long/Short/Instantaneous) trip curves, which will provide better flexibility of adjustment. The overload trip current should be set according to the input voltage, 220 V or 440 V. The use of electronic devices allows easier coordination and selectivity with other pieces of equipment.

The short circuit breaker rating should be according to the maximum three-phase current of the system in which the truck is connected. The suggested rating is 50 kA, which should cover most of the 440 V industries.

The Mobile EBA electrical system was modeled considering all loads required. The software used for the modeling was the Power System Software (PTW), manufactured by SKM System Analysis, Inc. The software allows the calculation of short circuit currents, validation of circuit breakers, graphical verification of the selectivity of current settings and calculation of the harmonic distortion ratio. Figure 3 shows the short-circuit analysis carried out.

Fig. 3. Electrical system model of the Mobile EBA
(0.7 MeV and 20 kW).



The short-circuit value in the 380 V busbar (metallic bar housed inside panel boards for local high current power distribution) is always limited by the 112.5 kVA transformer. The maximum short circuit obtained was 4.7 kA phase-to-ground that may seem low at first glance, but most manufacturers of low voltage circuit breakers produce equipment with interruption capacity of 3 kA. Therefore, for the mobile EBA circuit breakers, with a short-circuit rating equal to or greater than 5 kA, the 4.7 kA phase-to-ground should be chosen.

9 DIESEL GENERATOR

The diesel generator should be sized according to nominal load including harmonic’s content. Due to its high fuel consumption, it should be used only where the electrical connection is not possible. Considering the premise of non-continuous operation, the generator could be rated for 110 kVA stand by power, meaning that it has a limited operating time characteristic at the rated power.

As it is not possible to determine the generator's shelter conditions, an all-weather enclosure protection will be required. The control system of the generating unit should be local only and manually started. Since the Mobile Unit has several electric loads with high starting currents like the pumps, it is not recommended to start the generator with all the loads already connected, avoiding unnecessary transients that may reduce the equipment lifetime.

10 CABLE’S AND CIRCUIT BREAKER’S SIZING

The main circuit breaker should be equipped with an adjustable LSI electronic trigger, which allows easier coordination and selectivity plus good flexibility of settings. The overload trip current should be settable for both maximum and minimum currents, operating with 220 V and 440 V, respectively.

The symmetrical current interruption capability of the circuit breaker should be matched with the maximum three-phase short-circuit current of the system in which the truck is connected. As this value is unknown, a 36 kA capacity was suggested since it should be able to cover most 440 V systems.

Cable sizing procedures were in accordance with Brazilian and IEC standards. The voltage used in the calculations was the minimum available (220 V), since it results in higher losses and larger sections. .

The short circuit value considered was 50 kA (higher than the circuit breaker value). Therefore, for the established condition, a 120 mm² cable would support the short circuit without damage if its duration is less than 117 m. This time is acceptable, considering instantaneous trip time plus mechanical opening times.

The length was set based on some industries visited, where 100 m shall be enough for most of customers who want to receive the unit for wastewaters and effluents treatment. The summarized cable's final characteristics of the cables are presented in Table 3.

Table 3. Phases, sizes of protection cables and sections.

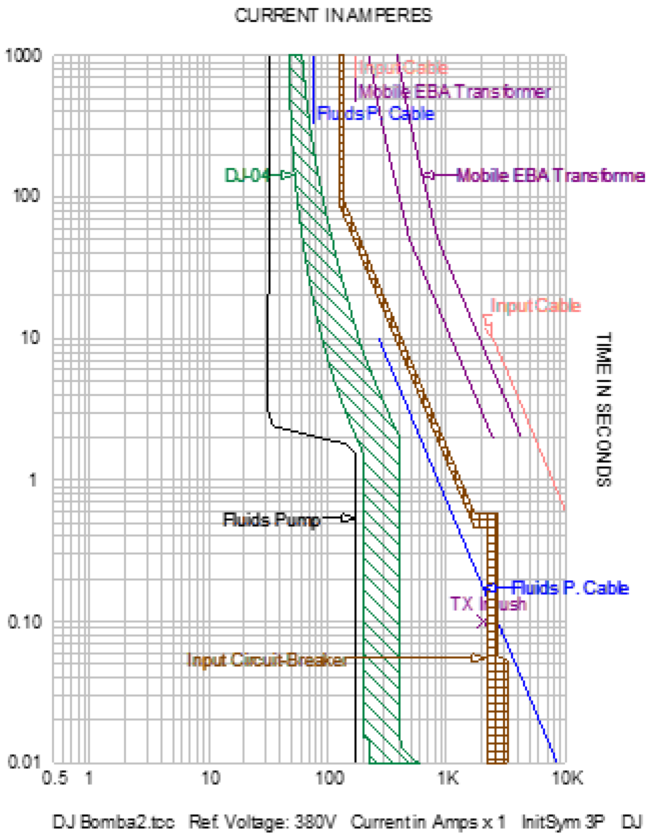
Application	Conductor		Length (m)	Insulation	
	Material	Section (mm²)		Type	Class (kV)
Phase	Copper	120 (3-poles)	100	EPR 90	0.6/1
Ground	Copper	70 (1-pole)	100	EPR 90	-

11 COORDINATION AND SELECTIVITY

Due to the unknown information according to the industry's circuit breakers, in which the Mobile Unit will be connected, achieving coordination and selectivity may not be an easy task. As an extra 112.5 kVA load will be added to the industry electrical system, some undesirable thermal overcurrents (overload) performance of the upstream circuit breaker may occur, incorrectly shutting down loads from the industry. Again, preliminary analysis of the local electrical system, by an engineer, is necessary before connecting the Mobile EBA Unit to the industry.

The input circuit breaker, with 300 A rated current and adjustable LSI type, should have a specific setting that guarantees the protection for overloads. Therefore, at each connected voltage, the electronic trigger should be set properly. The graphic coordination achieved from the mobile EBA devices are shown in Figure 4.

Fig. 4. Coordination achieved from the circuit breaker's LSI relay.



The mobile electron beam accelerator for the treatment of wastewater and industrial effluents is shown in Figure 5.

Fig. 5. Mobile Unit (0.7 MeV and 20 kW) developed by IPEN-CNEN.

12 CONCLUSION

Development and acquisition of all necessary electrical equipment and components for a Mobile Irradiation Unit, with an industrial EBA (0.7 MeV and 20 kW), is an important landmark to promote this nuclear technology, not widespread in Latin

America and the Caribbean. In this paper, the electrical cables, transformer, distribution boards and circuit breakers were dimensioned according to Brazilian IEC 61000-3-4 and IEEE-519 standards.

The main obstacle encountered was the impossibility of determining the electrical characteristics of the industrial plants, which the mobile EBA will be connected to. In order to ensure use in a wider variety of industries, all equipment has been sized to allow large short-circuit and voltage levels. In cases where there is no industrial voltage available for the Mobile EBA Unit (440/380/220 Volts), a diesel generator will be accessible for non-continuous demonstrations.

Harmonic injection generated by the Mobile Unit was analyzed by means of the direct measurement of the power quality of an EBA (1.5 MeV and 37.5 kW) installed at IPEN-CNEN. Due to the high values presented for the total harmonic distortion, the necessity to install filters to reduce the unwanted effects caused by the harmonics was identified.

The analyses performed in some industrial plants that could use the mobile electron beam accelerator indicate that it is not an easy task to add an extra load of 112.5 kVA, even in large industries, because of the electrical connection location, distance to the Mobile Unit and operating voltage, among others. It was demonstrated that, for each case, the analysis by an electrical engineer is essential in order to authorize or not the electrical connection in the industrial plant. A number of cautions have to be taken with the Mobile Unit, such as adjusting the primary connections of the isolating transformer and the curves of the circuit breaker, according to the operating voltage.

ACKNOWLEDGMENTS

Thanks to the IAEA, FINEP and IPEN-CNEN for technical, scientific and financial supports.

REFERENCES

[1] Calvo, W.A.P.; Duarte, C.L.; Machado, L.D.B.; Manzoli, J.E.; Geraldo, A.B.C.; Kodama, Y.; Silva, L.G.A.; Pino, E.S.; Poli, D.C.R.; Tobias, C.C.B.; Mathor, M.B.; Somessari, S.L.; Omi, N.M.; Somessari, E.S.R.; Silveira, C.G.; Rela, P.R.. Needs and Emerging Opportunities of Electron Beam Accelerators on Radiation Processing Technology for Industrial and Environmental Applications in South America. 2009. 18 p. International Topical Meeting on Nuclear Research Applications and Utilization of Accelerators, IAEA, Vienna, 4-8 May 2009.

[2] RELA, P.R. Development of na Irradiation Device for Electron Beam Wastewater Treatment. 2003. Thesis (Doctorate degree in Nuclear Technology) – Nuclear and Energy Research Institute (IPEN-CNEN). São Paulo.

[3] RELA, C. S. Study of Technical and Economical Feasibility for implementation of a movable unit for treatment of industrial effluents with electron beam. 2006. 76 p. Dissertação (Mestrado em Tecnologia Nuclear) – Nuclear and Energy Research Institute (IPEN-CNEN). Sao Paulo.

[4] IEC TS 61000-3-4:1998 Electromagnetic compatibility (EMC) - Part 3-4: Limits - Limitation of emission of harmonic currents in low-voltage power supply systems for equipment with rated current greater than 16 A.

[5] IEEE Std. 519-2014; IEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.

[6] IEEE Std. C57.110-2008; IEEE Recommended Practice for Establishing Liquid-Filled and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinuoidal Load Currents.

[7] SHARIFIAN, M.B.B; FAIZ, J.; FAKHERI, S.A Derating of distribuition transformers for non-sinusoidal load currents using finite element method. IEEE Article 2003. p. 754 – 757.