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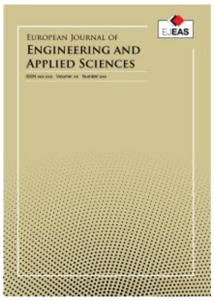

Research Article

Ampacity Decrease in a Three-phase Power Cable Fed by an Uncontrolled Rectifier and Finding a Lower Limit for the Power Cable Loss

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Abstract—Rectifiers are the most common nonlinear loads encountered in electrical power systems. Uncontrolled rectifiers are cheaper than synchronous rectifiers and more common than them because of this but the currents drawn by uncontrolled rectifiers contain harmonics. In addition, the amplitude of these harmonics depends on the value of the load power and the rectifier parameters. A 3-phase cable can be used to connect a three-phase rectifier to a 3-phase power system. In this study, the power losses of a 3-phase cable fed by a synchronous rectifier and an uncontrolled rectifier were compared. The electrical equivalent of a power cable is frequency dependent. The analysis performed in this study was made by making some assumptions about the frequency-dependent resistance of the cable and the rectifier currents. The analysis shows that when an uncontrolled rectifier is fed by a power cable, the cable always has more loss and heats up more for the same amount of RMS current.

Keywords—*Cable Modeling, Loss Calculation, Harmonic Analysis, Circuit Analysis, Rectifiers.*

Kontrolsüz Bir Redresörle Beslenen Üç Fazlı Bir Güç Kablosunda Amper Kapasitesinin Azalması ve Güç Kablosu Güç Kaybının Alt Değerinin Bulunması

Öz. Doğrultucular elektrik güç sistemlerinde en yaygın karşılaşılan nonlineer yüklerdir. Kontrolsüz doğrultucular senkron doğrultuculara göre daha ucuzdur ve bundan dolayı daha yaygındır ama kontrolsüz doğrultucuların çektikleri akımlar harmonik içermektedir. Ayrıca bu çekilen harmoniklerin genliği yükün gücünün değerine ve doğrultucu parametrelerine bağlıdır. Üç fazlı bir doğrultucuyu üç fazlı güç sistemine bağlamak için üç fazlı bir kablo kullanılabilir. Bu çalışmada senkron bir doğrultucu ve kontrolsüz bir doğrultucu tarafından beslenen üç fazlı bir kablodaki kayıplar karşılaştırılmıştır. Bir kablonun elektriksel eşdeğeri frekansa bağımlıdır. Bu çalışmada yapılan analiz kablonun frekansa bağımlı direnci ve doğrultucu akımları üzerine bazı kabuller yapılarak bulunmuştur. Yapılan analiz kontrolsüz doğrultucu kullanıldığında 3 fazlı kablonun her zaman daha fazla kayba sahip olduğunu ve daha fazla ısınacağını göstermektedir.

Anahtar Kelimeler— *Kablo Modelleme, Kayıp Hesabı, Harmonik Analizi, Devre Analizi, Doğrultucular.*

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1. Introduction

Electrical resistance is a function of frequency [1]. Skin-depth results in extra power loss in a cable excited with AC currents [2, 3]. Three-phase cables are complex systems to model [4]. Such transmission line models can also be made with fractional-order circuit elements [5]. This results in higher attenuation in high frequencies [3, 5, 6]. Such a frequency modeling of the cables may require machine learning [6]. The effects of harmonics on underground power cables are examined by considering a real system and using experimental data and shown to result in an excessive temperature rise due to the power losses in the cable [7]. Aging processes such as water treeing, electrical treeing, and dielectric breakdown can be observed in polymeric insulators of cables [8] and the high-temperature operation of cables also contributes to their early aging [9-11]. Cable failures and degradations that may occur directly or indirectly in the cable due to harmonics should be prevented [11, 12]. Skin and proximity effects in the cable impedance are difficult to model [13]. Their accurate modeling is also important in motor drive applications [14]. Three-phase power cables are often used to feed power rectifiers in industry. An experimental model of such a rectifier can be found in [15]. Uncontrolled rectifiers are nonlinear circuits, which lack exact analytical solutions [16] and are hard to model. That's why simplified models are often used in their analysis [17]. Some rectifiers use A frequency domain model for uncontrolled rectifiers as presented in [18]. A rectifier model for active loads is given in [19]. Averaging can also be used to model uncontrolled rectifiers [20]. A matrix solution for their modeling is presented in the frequency domain in [21]. An equivalent circuit for a diode bridge that makes use of AC and DC side rectifier harmonics is given in [22]. The uncontrolled rectifiers draw non-sinusoidal currents and their current profile varies by the load power [16-22] and this can cause overheating in the power cables. In this study, a lower bound for the power loss of a three-phase power cable feeding a three-phase uncontrolled rectifier is given to find out whether the loss stays the same for the same amount of transferred power to the load and whether the loss stays within the standards such as the international electrotechnical commission IEC 60287 standard [12].

The paper is arranged as follows. In the second section, the simplified models of an uncontrolled rectifier and a synchronous rectifier are given. In the third section, a lower value of the loss of power cable for an uncontrolled rectifier is given. The paper is finished with the conclusion section.

2. The Synchronous Rectifier and Uncontrolled Rectifier Models

A three-phase synchronous rectifier is a power electronic circuit, which uses the three-phase H-bridge inverter topology shown in Figure 1.a. Such rectifiers make use of sophisticated switching control strategies to withdraw almost sinusoidal currents from a three-phase utility with almost a power factor of one [23-26]. Since the harmonics around switching frequencies have very low magnitudes [27], their phase currents can be expressed as

$$i_a(t) = I_m sin(\omega t) \tag{1}$$

$$i_b(t) = I_m sin(\omega t - 2\pi/3) \tag{2}$$

$$i_c(t) = I_m cos(\omega t - 4\pi/3) \tag{3}$$

where I_m is the maximum value of the phase currents and ω is angular frequency.

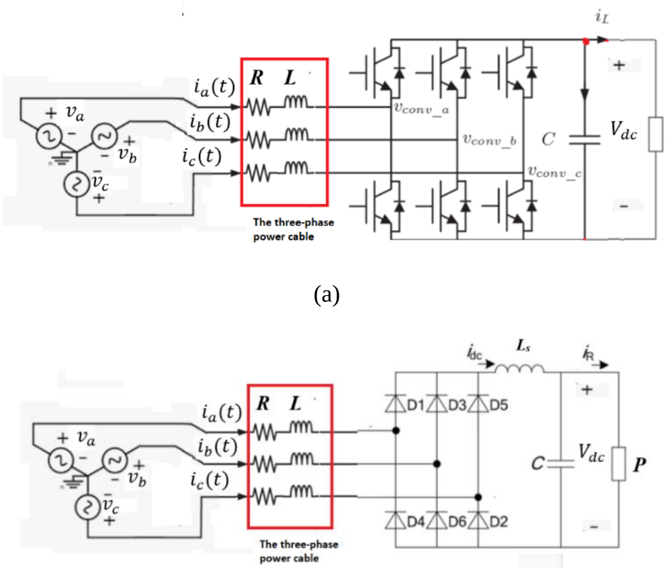
The three-phase phase voltages can be written as

$$v_a(t) = V_m sin(\omega t) \tag{4}$$

$$v_b(t) = V_m sin(\omega t - 2\pi/3) \tag{5}$$

$$v_c(t) = V_m sin(\omega t - 4\pi/3) \tag{6}$$

where V_m is the maximum value of the phase voltages.



(a)

(b)

Fig. 1. *a) A three-phase synchronous rectifier circuit, and b) A three-phase uncontrolled rectifier circuit.*

An uncontrolled Hs-bridge rectifier is shown in Figure 1.b. It consists of six diodes. It has a DC bus inductor or a smoothing inductor (***L_s***) at the DC side. The inductor and the capacitor across the load behave as an *L-C* filter. It does not have any smoothing inductors at the AC inputs. Such a rectifier circuit draws non-sinusoidal currents and their current varies with respect to the load power [16-22].

A DC bus smoothing inductor is commonly used for filtering the AC ripple in the DC bus current. If its inductance value is high enough, the DC bus current at a high load can be assumed to be constant [28]. Due to the symmetric nature of the three-phase H-bridge rectifier and having an almost constant DC bus current, a phase current pulse is drawn from 120 degrees in both of the half-periods and there are also 30 degrees wide dead zones for symmetrically drawn pulses. Such a phase current can be expressed with Eq. (7) by ignoring the very little cable inductance. If there were a smoothing inductor used on each line to smoothen the phase currents the rectifier draws, a tapered phase current expression that takes the commutation of phases into account should have been used. Since the inductances of the cables are quite less than that of such AC side smoothing inductors, Eq. (7) is sufficient to describe the phase current A.

At the maximum power with a smoothing inductor (L_s), whose inductance is sufficiently high, its Phase A current can be assumed to be of the form shown in Figure 2 and expressed as the following partial function:

$$i_a(t) = \begin{cases} 0, & 0 \leq t < \dfrac{T}{12} \\ I_{dc,} & \dfrac{T}{12} \leq t \leq \dfrac{5T}{12} \\ 0, & \dfrac{5T}{12} < t < \dfrac{7T}{12} \\ -I_{dc}, & \dfrac{7T}{12} \leq t \leq \dfrac{11T}{12} \\ 0, & \dfrac{11T}{12} < t \leq< T \end{cases} \qquad (7)$$

where I_{dc} is the DC bus inductor current and $T = 2\pi/\omega$ is the electrical period.

The other phase currents are shifted by 120 degrees but they have also the same rms value:

$$i_b(t) = i_a(t - T/3) \qquad (8)$$

$$i_c(t) = i_a\left(t - \frac{2T}{3}\right) = i_b\left(t - \frac{T}{3}\right) \qquad (9)$$

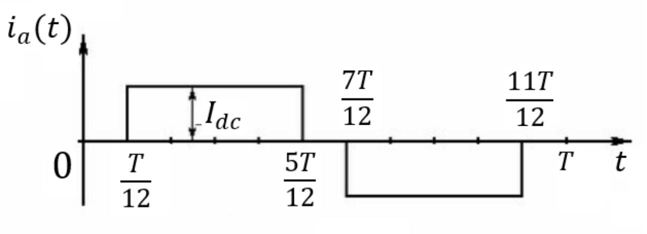


Fig. 2. *Phase A current of the uncontrolled rectifier.*

The DC bus inductor current can be assumed as

$$I_{dc} = \frac{P}{V_{dc}} \qquad (10)$$

where P is the load power and V_{dc} is the DC bus voltage.

The DC bus voltage of the uncontrolled rectifier is approximately given as

$$V_{dc} = \frac{3\sqrt{3}V_m}{\pi} = \frac{3\sqrt{6}V_{rms}}{\pi} \qquad (11)$$

The DC voltage of an uncontrolled three-phase H-Bridge rectifier can be around and less than the peak value of the line-to-line voltages, which is equal to 537 (380*sqrt(3)) Volt in Europe. Eq. (11) gives a value of 514 Volt, which is a little less than this value.

If the rectifier is loaded with the nominal power, the DC bus inductor current can be written as

$$I_{dc} = \frac{P_{nom}}{V_{dc}} \qquad (12)$$

The rectifier circuit currents at low load power are hard to predict and simulations can be used for this purpose that will be studied in the future.

3. The Estimation of the Cable Power Losses for the Two Cases

A three-phase power cable topology is shown in Figure 3. It has copper wires as power conductors, an aluminum shield, and PVE used as insulation material. The losses of the power cables for the rectifiers are to be calculated in this section.

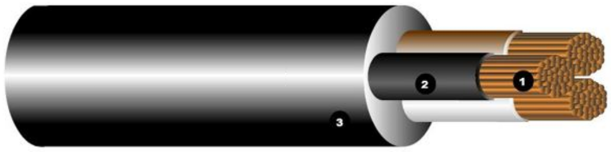


Fig. 3. *A three-phase power cable topology (Courtesy of Unika Cable).*

3.1. The Power Loss of a Three-Phase Cable under Sinusoidal Excitation or Fed by a Synchronous Rectifier

The nominal power which can be transferred through the power cable is given as

$$P_{nom} = 3V_{rms}I_{rms} = 3V_mI_m/2 \qquad (13)$$

where I_{rms} is the rated rms phase current, and V_{rms} is the rated rms phase voltage.

The rms current of the power cable for Phase A is calculated as

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T (i_a(t))^2 dt} \qquad (14)$$

For a sinusoidal current given in Eq. (1), the rms current is

$$I_{rms} = \frac{I_m}{\sqrt{2}} \qquad (15)$$

Thus, the nominal transferred power by the power cable can also be given as

$$P_{nom} = 3V_{rms}I_{rms} \qquad (16)$$

Since the phase currents of a synchronous rectifier are assumed to be sinusoidal, the power loss of the cable feeding the synchronous rectifier can be calculated as

$$P_{loss1} = 3R_{AC}I_{rms}^2 \qquad (17)$$

where R_{AC} is the AC resistance of the cable at the utility frequency, $f = 1/T$.

The AC resistance of a three-phase cable [12] can be given as

$$R_{AC} = R_{DC}(1 + ys + yp) \tag{18}$$

where R_{DC} is the DC resistance of the cable, ys is the skin effect factor, and yp is the proximity effect factor.

More about the AC resistance of a cable can be found in [29].

Using the transferred power,

$$P_{loss1} = 3R_{AC}\left(\frac{P_{nom}}{3V_{rms}}\right)^2 = \frac{R_{AC}P_{nom}^2}{3V_{rms}^2} = \frac{0.333R_{AC}P_{nom}^2}{3V_{rms}^2} \tag{19}$$

The rectifier circuit currents at low load power are hard to predict and simulations can be used for this purpose that will be studied in the future.

3.2 The Lower Bound of Power Loss of the Three-Phase Cable Fed by an Uncontrolled Rectifier

The uncontrolled rectifier is assumed to be drawing a current with harmonics from Phase A as seen in Figure 2. The other phase currents are shifted by 120 and 240 degrees with respect to the current of Phase A. The power loss of a cable is frequency dependent due to the skin and proximity effects:

$$P_{loss2} = 3\sum_{k=1}^{\infty}\frac{R_k I_k^2}{2} \geq 3\sum_{k=1}^{\infty}\frac{R_{AC}I_k^2}{2} = 3R_{AC}\sum_{k=1}^{\infty}\frac{I_k^2}{2} \tag{20}$$

where P_{loss2} is the power loss of the three-phase cable feeding the uncontrolled rectifier and R_k=R(kf) is the phase resistance of the three-phase cable at the k^{th} harmonic.

R_k is an increasing function of frequency. The cable resistance at the fundamental frequency (R_{AC} or R_1) is less than that at the k^{th} harmonic frequency (k≥2) and the following is always true,

$$R_k \geq R_{AC} = R_1 \tag{21}$$

Therefore, a lower bound for the power loss can be found as

$$P_{loss} = 3\sum_{k=1}^{\infty}\frac{R_k I_k^2}{2} \geq 3\sum_{k=1}^{\infty}\frac{R_{AC}I_k^2}{2} = 3R_{AC}\sum_{k=1}^{\infty}\frac{I_k^2}{2} \tag{22}$$

Using Parseval's identity,

$$I_{rms}^2 = \sum_{k=1}^{\infty}\frac{I_k^2}{2} = \frac{1}{T}\int_0^T (i_a(t))^2 dt \tag{23}$$

Using Eq. (7), the lower bound for the cable power loss can be calculated as:

$$P_{lossmin} = 3R_{AC}I_{rms}^2 == \frac{3R_{AC}}{T}\int_0^T (i_a(t))^2 dt = \frac{3R_{AC}}{T}\frac{2T}{3}I_{dc}^2 \tag{24}$$

$$P_{lossmin} = 2R_{AC}I_{dc}^2 = 2R_{AC}\left(\frac{P_{nom}}{V_{dc}}\right)^2 \tag{25}$$

$$P_{lossmin} = 2R_{AC}\left(\frac{P_{nom}}{\frac{3\sqrt{3}V_{rms}}{\pi}}\right)^2 = \frac{2\pi^2 R_{AC}}{27}\left(\frac{P_{nom}}{V_{rms}}\right)^2 \tag{26}$$

The lower bound of the power loss of the cable feeding the uncontrolled rectifier is found as:

$$P_{lossmin} = 0.731R_{AC}\left(\frac{P_{nom}}{V_{rms}}\right)^2 \tag{27}$$

Therefore, the following expression is always true:

$$P_{loss} > P_{lossmin} \tag{28}$$

Therefore, considering both of the cases examined, for the same value of the rms voltage, the following is always true:

$$P_{loss2} > P_{lossmin} > P_{loss1} \tag{29}$$

The power loss of the cable feeding the uncontrolled rectifier is always higher than that of a synchronous rectifier.

Ampacity is a made-up word for ampere capacity (current-carrying capacity) defined by National Electrical Codes [30], in some North American countries. Ampacity is defined as the maximum current, in amperes, that a conductor can carry continuously under the conditions of use without exceeding its temperature rating.

$$\frac{P_{loss2}}{P_{loss1}} > \frac{P_{lossmin}}{P_{loss1}} = 2.195 \tag{30}$$

This means to prevent overheating of the three-phase cable and not to decrease its life, the cable should be operated a lower current or transfer a lower power.

4. Conclusions

In this study, the losses occurring in a three-phase power cable feeding a synchronous and an uncontrolled rectifier have been examined. It is assumed that the rectifier has a DC side smoothing inductor and draws a square wave current with zero intervals. A lower bound value for the cable power loss feeding the uncontrolled rectifier is given. Considering (9) and (23), the power loss of the cable feeding the uncontrolled rectifier is at least 119.5% higher than that of the synchronous rectifier case. If the skin effect model of the cable is taken into account, the power loss of the cable feeding the uncontrolled rectifier would have been found to be higher. The finding here is of importance since it implies that the ampacity of the cable decreases, i.e., the cable overheats when the three-phase cable feeds an uncontrolled rectifier having non-sinusoidal currents for the same amount of the transferred power. This means that a power cable should be operated to feed a lower transferred power in a steady state. Otherwise, its operation life would be less than the one given in its catalog. Also, considering that the uncontrolled rectifier load can be temporarily higher than the nominal power for a short amount of time, this would result in an even higher temperature in the cable and the worst impact on his life.

A more accurate analysis of such a 3-phase cable should be performed by taking into account the transfer function in the frequency domain of the cable and the harmonics of the current. As future work, to obtain a more accurate loss model, we suggest that the experimentally measured cable parameters and the complete circuit model of the uncontrolled rectifier must be used to estimate the power loss. More sophisticated cable models can be used for that purpose [31]. The current harmonics of the input currents of the uncontrolled rectifier can be obtained by simulations depending on the load power, and, then, the cable losses can be calculated using the harmonic magnitudes and experimentally found cable parameters such as the frequency-dependent electrical resistance.

Smoothing inductors at AC side of the uncontrolled rectifiers are commonly used in the factories for power quality improvement. Also, using a smoothing inductor for each side at the AC side of the uncontrolled rectifier may result in the less power cable loss since the phase currents can be smoothened. We also suggest this as future work.

Author Contribution

Formal analysis –Reşat Mutlu (RM); Investigation – RM; Hakan Çanta (HÇ), Processing – RM, HÇ; Literature review – RM, HÇ; Writing – RM, HÇ; Review and editing – RM, HÇ;

Declaration of Competing Interest

The authors declared no conflicts of interest with respect to the research, authorship, and/or publication of this article.

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