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SIMULACIJA PREKIDAČKO-RELUKTANTNOG MOTORA
SWITCHED RELUCTANCE MOTOR SIMULATION

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Sažetak: *U ovome je radu opisan način rada i primjene prekidačko-reluktantnog motora (PRM). Predstavljene su linearna i nelinearna analiza stroja. Prikazana je simulacija strujno upravljivog 60* kW *motora u programskom paketu MATLAB-Simulink primjenom Power System Toolboxa.*

Ključne riječi:
– reluktantni moment
– induktivitet
– koenergija
– upravljački kutovi

Abstract: *This paper describes the operation mode of the switched reluctance motor (SWRM). Linear and non linear analyses are presented. In addition, a current-controlled 60* kW *switched reluctance machine is simulated with MATLAB-Simulink using Power System Toolbox.*

Keywords:
– reluctance torque
– inductance
– coenergy
– conduction angle

1. UVOD

Razvojem elektronike sredinom 1970-ih započinje intenzivniji razvoj motora naziva prekidačko-reluktantni motor (PRM) čiji su fizikalni principi djelovanja bili poznati davno prije. U tom razdoblju nastaju radovi koji tretiraju taj motor kao npr. [1-3]. Razvoj tog motora imao je za cilj da on bude kompetentan asinkronom motoru kako svojim karakteristikama tako i cijenom. Taj cilj predstavlja daljnji istraživački izazov sve do danas i potaknuo je brojne radove kao i primjenu PRM u industriji. U literaturi objavljenoj u Hrvatskoj taj je motor vrlo malo zastupljen. U Hrvatskoj postoji naime samo nekoliko istraživačkih i znanstvenih radova koji su nastali u razdoblju 1980–1990 [4-6]. Iz toga se razloga ovim radom želi predstaviti taj motor u našoj literaturi, s fizikalnom slikom načina rada i uz pomoć primjene novih alata, kao što je *Matlab-Power System Toolbox*, prikazati proračun karakteristika za pojedini motor.

2. OSNOVE DJELOVANJA STROJA

Reluktantni stroj je električni stroj u kojemu se moment proizvodi s tendencijom rotora da dospije u poziciju maksimalnoga induktiviteta uzbudnog namota.

1. INTRODUCTION

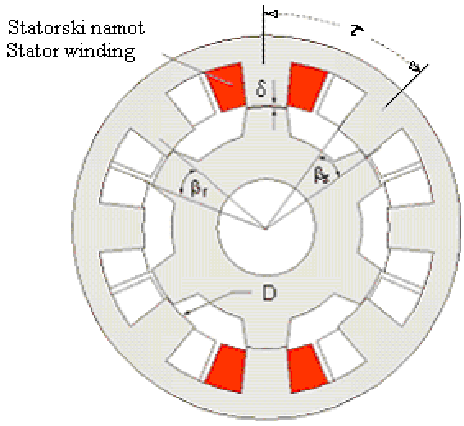
Intensified development of the SWRM was stimulated by the development of electronics in the mid 1970s; nevertheless, the physical principals of SWRM had in fact been discovered long before this time. During this period, works emerged that investigated this type of motor, as cited in examples [1-3]. The development of the SWRM was meant to accomplish a motor that would be competent for the induction motor both in its characteristics and in terms of pricing. This goal presents a constant research challenge to this day and initiates many continued studies and applications of this motor in the industry. The SWRM is seldom represented in Croatian sources and there are few existing research and scientific works on this subject that originate between the years 1980 and 1990 [4-6]. It is for this reason that the authors intend to present the SWRM in this study, through the application of such new calculation tools as the *Matlab-Power System toolbox*.

2. BASIC FUNCTIONING OF THE MOTOR

The reluctance motor is an electrical machine in which torque is produced with a tendency of the rotor to reach a position of maximal inductance of the excitation winding.

Ta definicija vrijedi za prekidačke i sinkrone reluktantne strojeve. Njih odlikuje vrlo jednostavna konstrukcija. Stroj ima istaknute polove i na statoru i na rotoru. Statorski namot sastoji se od niza koncentriranih zavojnica namotanih oko statorskih polova, dok na rotoru ne postoji nikakav namot. Postoje mnoge izvedbe PRM koje se razlikuju brojem faza te brojem statorskih i rotorskih polova. Na slici 1 prikazana je izvedba s $N_S = 8$ statorskih polova i $N_R = 6$ rotorskih polova pa tu izvedbu nazivamo i 8/6 prekidačko-reluktantni motor. Dužina zračnog raspora je δ, luk statorskog i rotorskog pola su β_S i β_R, dok je τ polni razmak na statoru. Na slici 2 prikazano je magnetsko polje za jednostavan reluktantni stroj na kojem će biti opisan osnovni princip generiranja momenta.

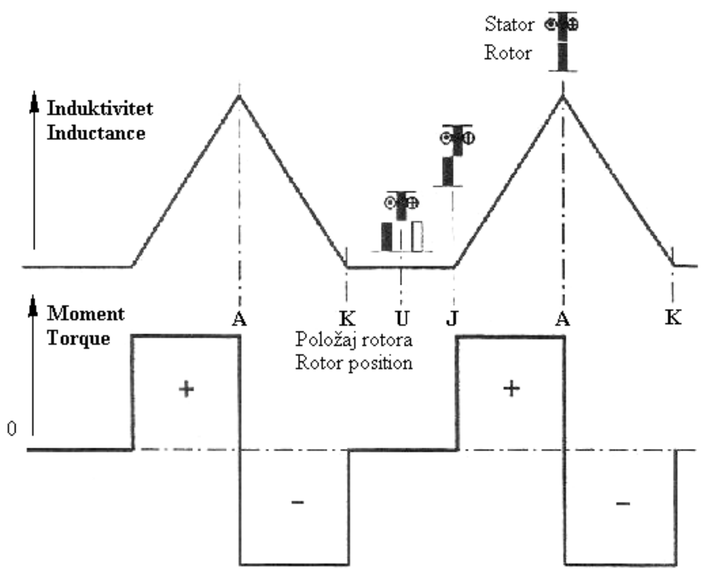
This definition holds true for both switched and synchronous reluctance motors. These motors have a very simple construction. The machine has salient poles on the stator and the rotor. The stator winding is made up of a series of concentrated coils wound around the stator poles, whereas on the rotor there are no coils. There are many versions of SWRM that differ in the number of phases and in the number of stator and rotor poles. Figure 1 shows performance where $N_S = 8$ stator poles and $N_R = 6$ rotor poles, and we call this construction an 8/6 switched reluctance motor. The length of the air-gap is δ, bend in the stator and rotor poles is β_S and β_R, while τ is the polar offset in the stator. Figure 2 presents the magnetic field of a basic model reluctance motor that is used to describe the basic principles of generating torque.



Slika 1. Poprečni presjek PRM 8/6
Figure 1. Cross-section of SWRM 8/6

Dvije zavojnice namotane na suprotne statorske polove spojene su u seriju te tvore fazni namot. Pobudom faznog namota stvara se magnetski tok. Taj stroj može proizvesti moment samo za ograničeni kut rotacije koji otprilike odgovara luku statorskog pola β_S. Na slici 2 prikazana je ovisnost induktiviteta zavojnice o položaju rotora za opisani jednostavni stroj. Pretpostavimo da je struja zavojnice konstantna. Stroj generira pozitivni moment samo dok induktivitet zavojnice raste tj. dok se rotor zakreće prema položaju maksimalne magnetske vodljivosti, tj. od pozicije J do A. Pozicija J označava početak prekrivanja polova statora i rotora, A označava maksimum prekrivanja, dočim pozicija K označava završetak prekrivanja. U položaju maksimalne magnetske vodljivosti moment mijenja predznak. Prolaskom toga položaja privlačne sile između polova generiraju kočni moment. Kako bi se eliminirao negativni moment, potrebno je isključiti struju u trenutku kada pol rotora prođe položaj maksimalne magnetske vodljivosti.

Two coils wrapped on opposite stator poles are connected in a series (and thus constitute) the phase winding. The excited phase winding creates the magnetic flux. This machine can produce torque only for a limited angle of rotation that approximately matches the bend in the stator pole β_S. Figure 2 shows the dependence of the inductance coil on the position of rotor for the basic machine described. It is assumed that coil current is constant. The machine generates positive torque only under an increase in coil inductance, i.e., while the rotor rotates from position J toward the position of maximum magnetic permeance A. Thus, position J defines the start of overlap for stator and rotor poles, A the maximum overlap, and K end of overlap. Torque indication changes when in a position of maximum permeance. Breakaway torque is generated upon passing the position of magnetic attraction between poles. In order to eliminate braking torque, it is necessary to turn off the machine at the moment when half of the rotor has passed the position of maximum permeance.



Slika 2. Ovisnost induktiviteta i momenta o položaju rotora pri konstantnoj struji zavojnice
Figure 2. Dependence of inductance on torque and position of the rotor under constant current in the coil

2.1. Linearna analiza stroja

Linearna analiza podrazumijeva nepostojanje magnetskog zasićenja. U tom slučaju induktivitet je neovisan o struji. Zbog jednostavnosti pretpostavit ćemo da sav tok prelazi zračni raspor u radijalnom smjeru. Međuinduktivitet između faza obično je vrlo mali te se također zanemaruje. Naponska jednadžba jedne faze je:

2.1. Linear machine analysis

Linear analysis implies the absence of magnetic saturation. In such a case, inductance is independent of current. For the sake of simplicity, we will assume that the total flux crosses the air-gap in a radial direction. Mutual-inductance between phases is usually very small and it is often neglected. The voltage equation for a single phase is as follows:

$$u = Ri + \frac{d\psi}{dt} = Ri + \omega_m \frac{d\psi}{d\Theta} \tag{1}$$

$$= Ri + \omega_m \frac{d(Li)}{d\Theta} = Ri + L\frac{di}{dt} + \omega_m i \frac{dL}{d\Theta},$$

gdje je u napon na stezaljkama, i je struja, a ψ ulančani tok, R je otpor, a L induktivitet faze, θ je pozicija rotora, a ω_m je kutna brzina u rad/s. Zadnji član u izrazu (1) je inducirani napon rotacije e:

where u is the voltage, i is current, and ψ is the flux linkage, R is the resistance, and L is the phase inductance, while θ is the position of the rotor, and ω_m is the angular speed in rad/s. The last expression (1) is the induced voltage of rotation e:

$$e = \omega_m i \frac{dL}{d\Theta}. \tag{2}$$

Trenutačna električna snaga je:

At any instant electrical power is:

$$ui = Ri^2 + Li\frac{di}{dt} + \omega_m i^2 \frac{dL}{d\Theta}, \tag{3}$$

Vremensku promjenu pohranjene magnetske energije u svakom trenutku možemo odrediti kao:

Time changes of the stored magnetic energy can be determined:

$$\frac{d}{dt}\left(\frac{1}{2}Li^2\right) = \frac{1}{2}i^2\frac{dL}{dt} + Li\frac{di}{dt} = \frac{1}{2}\omega_m i^2\frac{dL}{d\Theta} + Li\frac{di}{dt}. \quad (4)$$

Prema zakonu očuvanja energije, ako od ulazne snage *ui* oduzmemo omske gubitke Ri^2 i vremenski stupanj promjene pohranjene magnetske energije, dobivamo mehaničku snagu $p = \omega_m * T_e$. Prema tome iz jednadžbi (3) i (4) slijedi izraz za trenutačni elektromagnetski moment:

According to T*he Law of Conservation of Energy*, if we subtract ohm losses Ri^2 and the rate of change of magnetic stored energy from the energy input *ui*, we get a mechanical torque of $p = \omega_m * T_e$. Therefore, from formulas (3) and (4) the following expression for instantaneous electromagnetic torque is:

$$T_e = \frac{1}{2}i^2\frac{dL}{d\Theta}. \quad (5)$$

Za taj tip nezasićenog motora, manje od polovine energije dobivene od ulaznoga električnog kruga pretvara se u mehanički rad, čak i ako zanemarimo gubitke. Ostatak energije je energija pohranjena u magnetskom polju zavojnice. Energija pohranjena u polju svoju maksimalnu vrijednost dostiže u položaju *A*, a na kraju svakog ciklusa mora biti vraćena izvoru. Vraćanje energije vrši se komutiranjem struje kroz diode, kako bi se napon reverzirao i prisilio ulančani tok da padne na nulu [7, 8].

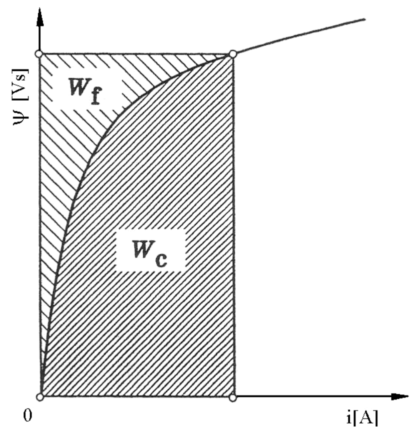
For this type of unsaturated motor, less than half of the energy obtained from the electrical circuit is converted into mechanical work, even if we are to disregard any losses. The remaining energy is stored in the magnetic field of the coil. The energy stored into the field achieves its maximal value in position *A*, and at the end of each cycle it must be returned to the source. The return of energy is carried out as the current commutes through the diode, in order that the voltage can be reversed, thus forcing the concatenated flux to fall to zero [7, 8].

2.2. Nelinearna analiza stroja

Iz prethodnog je razmatranja vidljivo da nezasićeni (tj. magnetski linearan) PRM ima nizak omjer faktora iskoristivosti i nisku iskoristivost upravljačkog sklopa. PRM za praktičnu primjenu imaju veći stupanj korisnog djelovanja, ali su i izrazito nelinearni. U nastavku će biti razmatrana nelinearna analiza temeljena na krivuljama magnetiziranja.

2.2. Nonlinear machine analysis

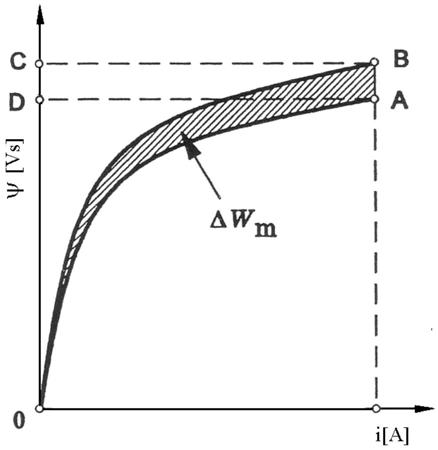
From the previous observations, it becomes apparent that the unsaturated (i.e., magnetically linear) SWRM has a low factor of efficiency and low efficiency of the controller. For practical purposes, switched reluctance motors have a higher efficiency, but they are nonlinear. The following section will cover nonlinear analysis based on magnetization curves.



Slika 3. Pohranjena magnetska energija W_f i koenergija W_c
Figure 3. Stored magnetic energy W_f and coenergy W_c

U dijagramu prema slici 3. prikazane su pohranjena magnetska energija W_f i koenergija W_c. Kod magnetski linearnih uređaja, krivulja magnetiziranja je pravac, pa je $W_f = W_c$. Rezultat zasićenja je $W_f < W_c$.

Stored magnetic energy W_f and coenergy W_c are shown in diagram in Figure 3. With the linear magnetic device, the magnetization curve is linear, represented by $W_f = W_c$. The results of saturation are $W_f < W_c$.



Slika 4. Određivanje elektromagnetskog momenta
Figure 4. Determination of electromagnetic torque

Pri pomaku Δθ ili *AB* uz konstantnu struju (slika 4), energija izmijenjena s izvorom je:

In the event of a shift of Δθ or *AB* with constant current (Figure 4), the energy exchanged from the source is:

$$\Delta W_e = \int eidt = \int i\frac{d\psi}{dt}dt = \int id\psi = ABCD, \tag{6}$$

a promjena pohranjene magnetske energije je:

and the change in stored magnetic energy is:

$$\Delta W_f = OBC - OAD. \tag{7}$$

Pri tome izvršeni mehanički rad je:

In which case the following mechanical work is carried out:

$$\Delta W_m = \Delta W_e - \Delta W_f \tag{8}$$

$$= OAB.$$

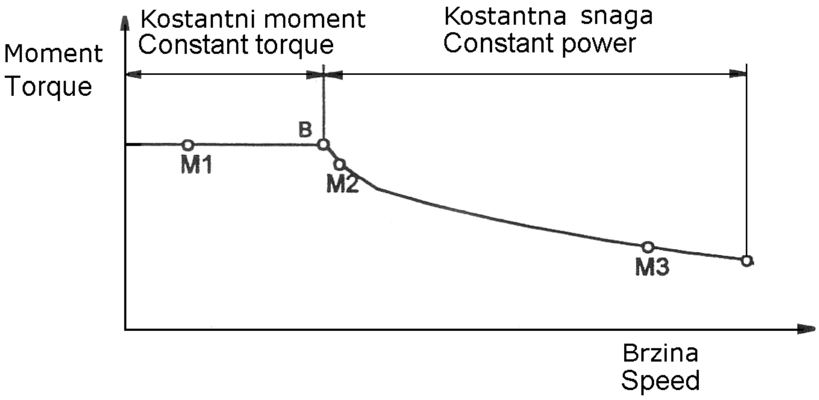
Izraz (8) jednak je $T_e\Delta\theta$, te u graničnom slučaju kada $\Delta\theta \rightarrow 0$ vrijedi:

Expression (8) is equivalent to $T_e\Delta\theta$, as well as in the extreme case when $\Delta\theta \rightarrow 0$ equals:

$$T_e = \frac{\partial W_c}{\partial \Theta}\Big|_{i=const.} \tag{9}$$

3. MOMENTNA KARAKTERISTIKA

Na slici 5 prikazana je momentna karakteristika prekidačko-reluktantnog stroja.



Slika 5. Momentna karakteristika
Figure 5. Torque characteristics

Područje konstantnog momenta. Bazna brzina je najveća brzina pri kojoj, uz nazivni napon, možemo postići maksimalnu struju i nazivni moment. U tome području upravljanje momentom vrši se regulacijom struje, uz minimalne prilagodbe kuta uključivanja koje su potrebne kako bi se poboljšali valni oblici struje ili momenta ili kako bi se popravio stupanj korisnog djelovanja.

Područje konstantne snage. Kako se brzina i inducirani napon povećavaju, kut vođenja tranzistora također se povećava kako bi se vršna vrijednost ulančanog toka održala na najvećoj mogućoj vrijednosti. Povećavanjem kuta vođenja proporcionalno brzini vršnu vrijednost ulančanog toka možemo održavati na istoj razini sve do brzine koja je otprilike dvaput veća od bazne brzine.

Područje smanjivanja snage. Daljnjim povećanjem brzine, kut uključivanja nije moguće više povećavati, te moment počinje sve brže opadati tako da se snaga više ne može održavati konstantnom. Ako kut uključivanja povećamo toliko da kut vođenja postane jednak otprilike polovici rotorskoga polnog koraka, vođenje će postati kontinuirano. Posljedica toga je da će se moment po amperu povećati. Zbog toga se pri kontinuiranom vođenju javlja mogućnost povećanja gustoće snage, ne samo pri velikim, već i pri malim brzinama. Negativna strana je povećanje gubitaka u bakru, što je prihvatljivo ako je dobitak u pretvorenoj snazi veći i ako stroj može izdržati povećanje temperature.

3. TORQUE CHARACTERISTICS

Figure 5. illustrates the torque characteristics of the switched reluctance motor.

Region of constant torque. The base speed is the highest speed at which (along with voltage rating) maximum energy and torque rating can be achieved. It is this region of torque control in which current regulation is carried out with minimal adjustment to the turn-on angles that is necessary to improve the current waveform or torque that in turn improves the efficiency factor.

Region of constant power. As speed and induced voltage increase, the conduction angle of the transistor also increases in order to maintain the maximum value of the flux linkage at the highest possible level. By increasing the conduction angle in proportion to speed, the maximum value of the flux linkage can be maintained at a constant level all the way up to a speed that is approximately two times higher than the base speed.

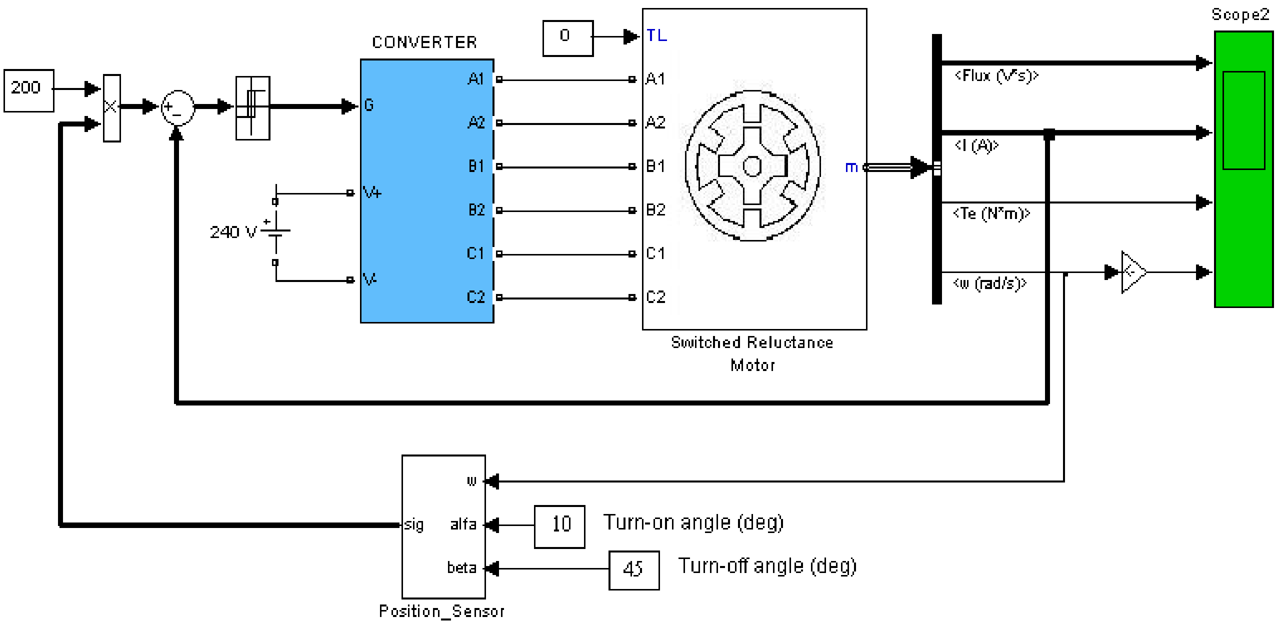
Region of power reduction. The turn-on angle cannot be increased by a further increase in speed, and torque begins to drop increasingly such that power can no longer remain constant. Insofar as the turn-on angle increases such that the conduction angle becomes equivalent to approximately one-half of the rotor pole pitch, then conduction can become continuous. The result of this is that the torque per ampere increases. For this reason, the possibility of an increase in power density under continuous conduction is enabled for both fast and slow speeds. The negative aspect of this is an increase in copper loss, which is acceptable insofar as there is a gain in converted power to the extent that the machine is able to withstand any increase in temperature.

4. SIMULACIJA PRM U MATLAB-SIMULINKU

Slika 6 predstavlja simulacijsku shemu pogona sa strujno upravljivim 60 kW 6/4 PRM kreiranu u *Matlab Power System Toolboxu* [9]. Motor se napaja trofaznim istosmjernim pretvaračem, pri tome svaka faza ima dva IGBT-a i dvije diode. Na rotor motora pričvršćen je senzor pozicije koji služi za određivanje točnoga redoslijeda uključivanja pojedinih faza. Faznim strujama upravlja se odvojeno pomoću tri regulatora koji upravljačke signale IGBT-a generiraju uspoređujući trenutačnu i referentnu vrijednost struje.

4. SIMULATION OF THE SWRM USING MATLAB-SIMULINK

Figure 6 represents an energy conversion scheme for a current-controlled 60 kW 6/4 SWRM created in *Matlab Power System toolbox* [9]. The motor is driven by a triphasic converter, wherein each phase has two IGBTs and two diodes. A position sensor is fastened to the rotor, which serves to determine the precise sequence of the switch on of particular phases. Phase currents are separately controlled by way of three regulators that generate the IGBT control signals by comparing the actual and referential values of the current.



Slika 6. Simulacijska shema pogona sa 60 kW *6/4 PRM*
Figure 6. Schematic drive diagram of a 60 kW *6/4 SWRM*

4.1. Rezultati simulacija

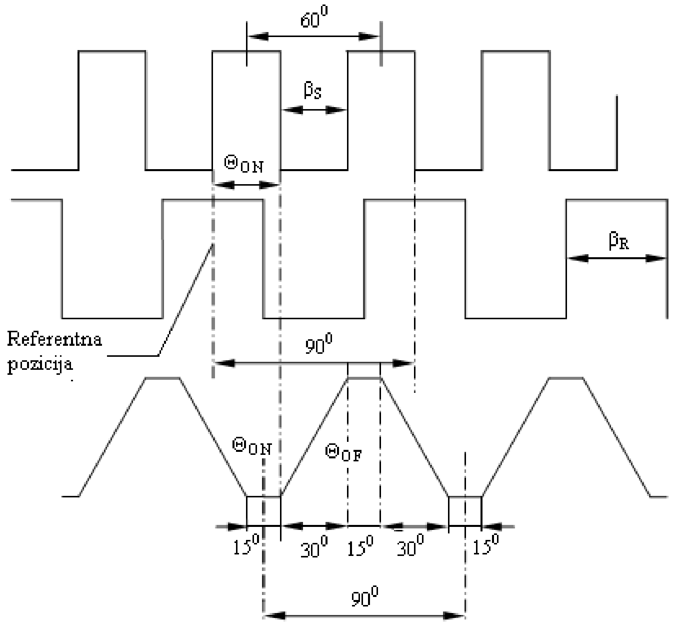
U ovom primjeru za napajanje se koristi naponski DC izvor, napona napajanja 240 V. Strujna referenca je 200 A, a pojas histereze strujnih regulatora je ±10 A. Za n = 1000 okr/min pretvarač radi u prekidačkom načinu rada s frekvencijom prekidanja struje od 7 kHz. PRM se pokreće davanjem step-signala kao reference na ulaz regulatora. Kako reguliramo samo struje, brzina motora će rasti u ovisnosti o dinamici mehaničkoga dijela sustava. Cilj simulacija je ustanoviti utjecaj promjena kuta uključivanja i isključivanja poluvodičkih sklopki na valne oblike struje, ulančanoga toka, a ponajviše momenta. Promjenom opterećenja motora dobiva se uvid u dinamičke značajke stroja.

4.1. Simulation results

In this example of power supply, a DC source is used, with a power supply of 240 V. The current reference is 200 A, and the hysteresis of the current controller is ±10 A. For n = 1000 rpm, the converter operates in switching mode with a switching frequency of 7 kHz. The SWRM is driven by sending a step signal as a reference point at the controller entry. As the machine is regulated, the motor speed increases in its dependence on the dynamics of the mechanical system. The goal of simulation is to determine the influence of a change in the turn-on angle and the turn-off angle of the semiconductor circuit on the waveform of the machine, and in particular on flux linkage and torque. With a change in the load on the motor, insight can be gained into the dynamic characteristics of this machine.

Prikaz referentne pozicije rotora prema kojoj se određuju iznosi upravljačkih kutova vidljiv je na slici 7. Prikazan je dio statora i dio rotora u razvijenoj dužini, odgovarajući profil induktiviteta i označena je referentna pozicija. U ovome primjeru širina pola statora $\beta_S = 30°$, dok je širina pola rotora $\beta_R = 45°$.

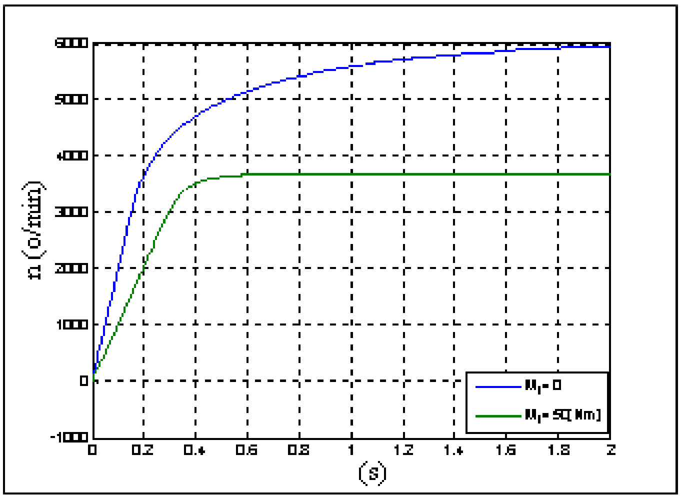
Figure 7 shows the reference positions of the rotor by means of which the values of the control angles are determined. Part of the stator and part of the rotor as the inductance profile are shown as well, with the reference position being marked. In this example, the width of the stator pole is $\beta_S = 30°$, while the width of the rotor pole is $\beta_R = 45°$.



Slika 7. Definiranje referentnog položaja rotora
Figure 7. Defining the referential position of the rotor

a) Na slici 8 prikazana je karakteristika zaleta pri opterećenju motora $T_l = 0$ i $T_l = 50$ Nm. Kut vođenja je $\Delta\theta = 35°$, $\theta_{ON} = 10°$ i $\theta_{OFF} = 45°$.
Maksimalna brzina neopterećenog motora približno je dvostruko veća od brzine opterećenog motora. Vrijeme potrebno za zalet neopterećenog motora (do vrijednosti za brzinu koju postiže opterećeni motor) je manje u usporedbi s opterećenim motorom. Posljedica je to nepostojanja momenta tereta koji se suprostavlja momentu motora. U tom slučaju, zanemarimo li trenje, sav moment motora utrošen je na ubrzavanje. Za opterećeni motor brzina je određena momentom tereta, te motor prestaje s ubrzavanjem kada se moment motora i moment tereta izjednače. Za vrijeme zaleta, do otprilike 3000 okr/min, srednje vrijednosti momenta motora bit će približno jednake za oba slučaja. Na kraju zaleta, kada motor postigne stacionarno stanje, srednja vrijednost momenta neopterećenog motora značajno je manja u usporedbi s opterećenim motorom.

a) Figure 8 illustrates the motor starting characteristics during motor load $T_l = 0$ and $T_l = 50$ Nm. The conduction angle is $\Delta\theta = 35°$, $\theta_{ON} = 10°$ and $\theta_{OFF} = 45°$.
Maximum speed of the unloaded motor is nearly twice as fast as that of the speed of the loaded motor. The time necessary for starting of the unloaded motor (up to the value of speed reached by the loaded motor) is less in comparison to that of the loaded motor. The result of this is the absence of load torque, which offsets motor torque. In this case, if friction is neglected, all motor torque is applied to accelerating. For the loaded motor, the speed is determined by the torque load, thus the motor ceases to increase in speed when motor torque and load torque become equivalent. During starting, up to approximately 3000 rpm, the average of motor torque will be about equal in both cases. At the end of starting process, when the motor reaches the stationary state, the average value of torque for the unloaded motor is significantly less than in comparison with the loaded motor.



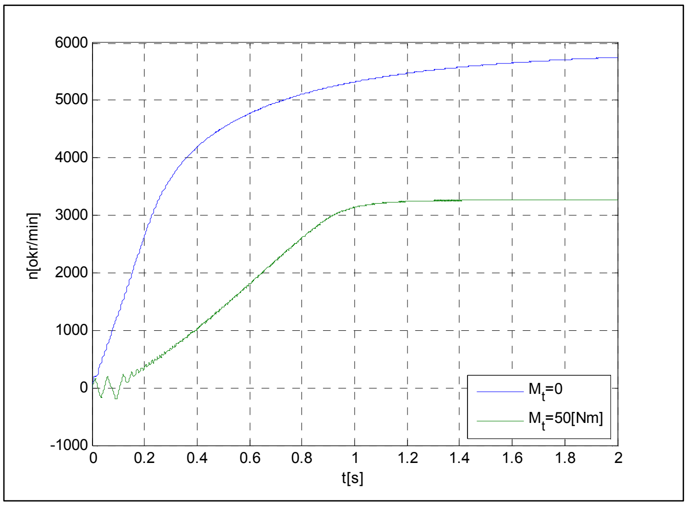
Slika 8. Zalet pri opterećenju $T_l = 0$ i $T_l = 50$ Nm; $\theta_{ON} = 10°$, $\theta_{OFF} = 45°$.
Figure 8. Starting characteristic under load $T_l = 0$ and $T_l = 50$ Nm; $\theta_{ON} = 10°$, $\theta_{OFF} = 45°$.

b) Na slici 9 prikazano je vrijeme zaleta za momente tereta $T_l = 0$ i $T_l = 50$ Nm. Kut vođenja je $\Delta\theta = 25°$, $\theta_{ON} = 10°$ i $\theta_{OFF} = 35°$

Kut vođenja $\Delta\theta$, te kutovi θ_{ON} i θ_{OFF} ostaju nepromijenjeni za obje vrijednosti momenta opterećenja. Međutim u odnosu na primjer a) kut θ_{OFF} je smanjen na 65°, te je samim time i kut vođenja $\Delta\theta$ smanjen na 25°. Na taj smo način za generiranje momenta iskoristili manji dio ukupno raspoloživog područja rastućeg induktiviteta nego u primjeru a). Posljedica toga bit će smanjenje srednje vrijednosti generiranog momenta, te će se vrijednosti brzina i ubrzanja smanjiti u odnosu na prethodni primjer.

b) Figure 9 shows the motor starting characteristic for load torque $T_l = 0$ and $T_l = 50$ Nm. The conduction angle is $\Delta\theta = 25°$, $\theta_{ON} = 10°$ and $\theta_{OFF} = 35°$

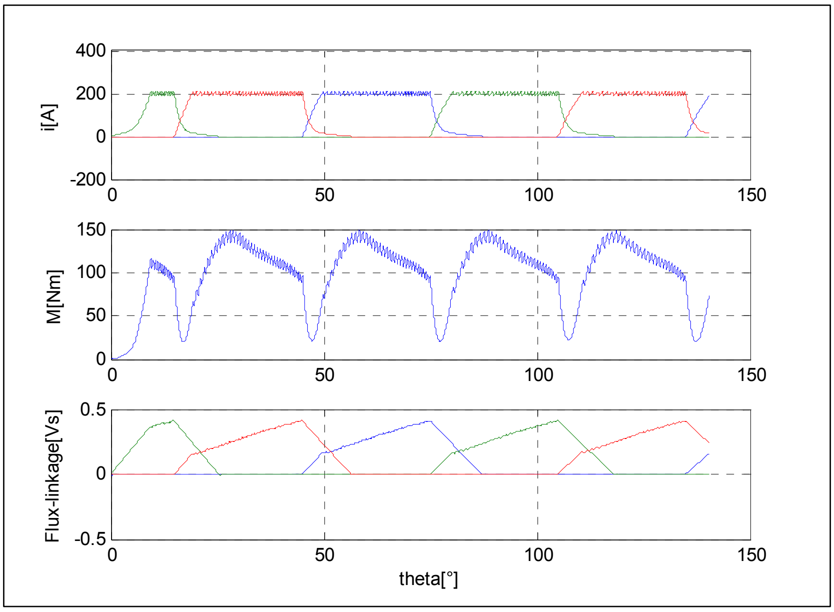
The conduction angle $\Delta\theta$, and the angles θ_{ON} and θ_{OFF} remain unchanged for both values of torque load. Nonetheless, in relation to example a) angle θ_{OFF} is reduced to 65°, and in this way the conduction angle $\Delta\theta$ is reduced to 25°. A lesser part of the total available region of growing inductance is thereby used for generating torque in comparison with example a). The result of this will be a lesser midrange value of generated torque, and the speed value and momentum will decrease in relation to the previous example.



Slika 9. Zalet pri opterećenju $T_l = 0$ i $T_l = 50$ Nm; $\theta_{ON} = 10°$, $\theta_{OFF} = 35°$
Figure 9. Starting characteristic under load $T_l = 0$ and $T_l = 50$ Nm; $\theta_{ON} = 10°$, $\theta_{OFF} = 35°$

c) Na slici 10 prikazani su valni oblici struje, momenta i ulančanog toka za opterećeni motor; $\Delta\theta = 30°$, $\theta_{ON} = 15°$ i $\theta_{OFF} = 45°$.

c) Figure 10 shows the waveforms of current, torque and flux linkage for the loaded motor; $\Delta\theta = 30°$, $\theta_{ON} = 15°$ and $\theta_{OFF} = 45°$.



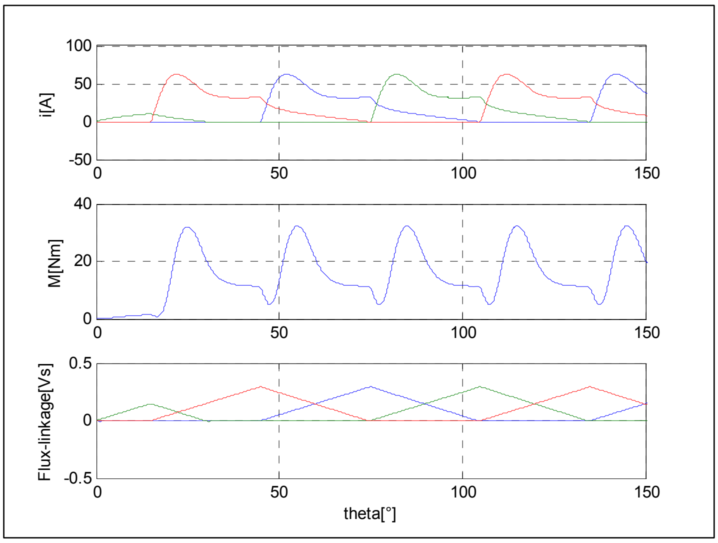
Slika 10. Valni oblici motora; n = 1000 o/min, $\theta_{ON} = 15°$, $\theta_{OFF} = 45°$
Figure 10. Motor waveforms; n = 1000 rpm, $\theta_{ON} = 15°$, $\theta_{OFF} = 45°$

U ovom režimu rada motor radi u rasponu brzina od 0 do otprilike 3000 [o/min]. U tom području brzina inducirani napon motora je nizak tako da struja može dostići referentnu vrijednost te se struja regulira prekidanjem. U valnom obliku momenta se osim valovitosti zbog prelaska struja između faza javlja i valovitost uzrokovana prekidanjem poluvodičkih sklopki. To područje rada naziva se i područje konstantnog momenta.

d) n = 4000 o/min, $\theta_{ON} = 15°$, $\theta_{OFF} = 45°$
Na brzinama iznad 3000 okr/min inducirani napon znatno se povećava, kut vođenja prelazi se u vrlo kratkom vremenu tako da struja ne može postići referentnu vrijednost. Kako bi struja imala što više vremena za porast, u tom režimu nema prekidanja sklopki, već one ostaju uključene tijekom cijeloga intervala generiranja momenta. Prema slici 11, vidimo da je srednja vrijednost momenta vrlo mala, što potvrđuje potrebu optimizacije kutova na velikim brzinama, ne samo zbog valovitosti momenta nego i za postignuće potrebnog iznosa momenta.

In this mode, the motor operates within a speed range between 0 and approximately 3000 rpm. In this region of speed, induced voltage is low to such a degree that the current can reach a referential value and can therefore be controlled by turning off. In the torque waveform, besides ripple, caused by the current transfer between phases, torque displays ripple caused by the current switching-off. This region of operation is furthermore called the region of constant momentum.

d) n = 4000 rpm, $\theta_{ON} = 15°$, $\theta_{OFF} = 45°$
At speeds above 3000 rpm, induced voltage is considerably increased and the conduction angle transfers over a short period in such a manner that the current cannot achieve the referential value. In order that the current can achieve the greatest possible time for increase, this mode has no turn-off switch, rather switches remain turned on throughout the entire interval of generated torque. According to Figure 11, it can be observed that the average value of torque is very small, which confirms the need for optimization of angles at high speeds, not only due to torque ripple but also in view of achieving the required amount of torque.



Slika 11. Valni oblici struje, momenta i ulančanog toka; n = 4000 o/min, $\theta_{ON} = 15°$, $\theta_{OFF} = 45°$
Figure 11. Waveforms of the current, torque and flux linkage; n = 4000 rpm, $\theta_{ON} = 15°$, $\theta_{OFF} = 45°$

5. ZAKLJUČAK

Opisan je način rada prekidačko-reluktantnog motora. Taj je motor razvijan kao konkurencija za asinkroni motor. Optimiranjem upravljanja kao i zahvatima na samoj geometriji stroja može se valovitost momenta smanjiti. Strujno upravljivi 60 kW 6/4 PRM simuliran u programskom paketu *MATLAB* primjenom *Power System Toolboxa*. Prikazani su rezultati simulacije zaleta za različita opterećenja i kutove vođenja. Također je prikazan i utjecaj promjene kutova uključivanja i isključivanja na valne oblike struje, momenta i ulančanog toka. PRM simuliran je za različite brzine vrtnje u području kostantnog momenta i u području kostantne snage.

5. CONCLUSION

The operating of the switched reluctance motor is herein described. This motor is developed as competition to the asynchronous motor. Optimizing control as well as alterations in the geometry of the machine itself can serve to reduce torque ripple. A current-controlled 60 kW 6/4 SWRM is simulated in the program package *MATLAB* using the *Power System Toolbox*. Starting characteristics are shown for various loads and conduction angles. In addition, the change in turn-on and turn-off angles and how this affects the waveform shapes of the current, torque and flux linkage is demonstrated. SWRM is simulated for various speeds of rotation in the regions of constant torque and constant power.

6. POPIS OZNAKA / 6. LIST OF SYMBOLS

luk statorskog pola	β_S – °	stator pole pitch
luk rotorskog pola	β_R – °	rotor pole with
polni korak	τ – °	pole pitch
napon	u – V	voltage
struja	i – A	current
ulančani tok	ψ – V_s	flux linkage
otpor faze	R – Ω	phase resistance
induktivitet faze	L – H	phase inductance
pozicija rotora	θ – °	rotor position
kutna brzina rotora	ω_m – rad/s	rotor speed
magnetska energija	W_f – J	magnetic energy
ko-energija	W_c – J	coenergy
moment motora	T_e – Nm	motor torque
moment tereta	T_l – Nm	load torque
kut uključivanja	θ_{ON} – °	switching on angle
kut isključivanja	θ_{OFF} – °	switching off angle
kut vođenja	Δθ – °	conduction angle

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